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The investigation of valve operators' torque production capabilities and optimal handwheel height, angle, and opening technique

Saif K. Al-Qaisi
Louisiana State University and Agricultural and Mechanical College, saif.qaisi.1@gmail.com

THE INVESTIGATION OF VALVE OPERATORS' TORQUE PRODUCTION CAPABILITIES AND OPTIMAL HANDWHEEL HEIGHT, ANGLE, AND OPENING TECHNIQUE

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Saif Al-Qaisi
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LIST OF ABBREVIATIONS

BH: Bare hands

CW-R: Conventional Wrench-Restricted

CW-U: Conventional Wrench-Unrestricted

DC: Duty Cycle

MAE: Maximum acceptable effort

MAF: Maximum acceptable force

MAT: Maximum acceptable torque

RC: Reference contraction (also known as maximum voluntary contraction or MVC)

ABSTRACT

This research consists of two projects concerned with handwheel-valve operations. The objectives of poject-1 were to: (1) introduce an ergonomically-modified valve-wrench and compare it to conventional valve-opening methods, in terms of efficiency (time to open valve), perceived physical exertion (Borg-scale), and muscle loading of shoulder and trunk muscles; and (2) determine whether the torque setting (15 Nm and 30 Nm) of the valve affects the preferred valve-opening method. Four methods were evaluated, including using bare hands (BH), conventional wrench-restricted (CW-R, assumes presence of obstructions), conventional wrench-unrestricted (CW-U, assumes no obstructions), and modified wrench (MW). Electromyography (EMG) activities were measured from the right and left anterior deltoids, trapezii, latissimi dorsi, and erector spinae muscles. The EMG activity of each muscle was normalized to the maximum EMG activity of the corresponding muscle's reference contraction (RC). This study used new RC procedures for the anterior deltoids and trapezii that were associated with higher EMG amplitudes than the RC procedures found in the literature. The valve-opening method that was associated with the lowest overall EMG activities was CW-R, followed by BH, MW, and finally CW-U. According to the time recordings and Borg-ratings, the MW was the most efficient and least physically demanding method in opening the valve.

The objectives of project-2 were to: (1) investigate operators' torque production capabilities and recommend maximum torque limits for different handwheel heights (knee, elbow, shoulder, and overhead levels) and angles (0^o, 45^o, and 90^o); and (2) determine an optimal handwheel height and angle, in terms of operators' maximum isometric torque exertions and the EMG activities of the same shoulder and trunk muscles as in project-1. The average maximum torque exertions ranged between 51.6 Nm (at overhead 0^o) and 74.9 Nm (at overhead 45^o) depending on

the height and angle of the handwheel. Through calculating the 5th percentile torque strength values of the female participants, this study recommends maximum torque limits ranging between 13.7 Nm and 24.1 Nm, depending on the height and angle of the handwheel. Analysis of the results indicates that the optimum height and angle of a handwheel is at shoulder level and zero degree.

CHAPTER 1: INTRODUCTION

Cracking, opening, and closing handwheel-valves are common tasks to various industries. Some of the different workplaces that utilize handwheels are the power generation, water supply, petroleum refinement, railway, and chemical and waste industries (Woldstad et al., 1995; Meyer et al., 2000; Amell and Kumar, 2001). Handwheel actuation is primarily used to regulate the flow of material within a valve system, such as steam, oil, refrigerant, and fly ash (Mead, 1986). Handwheels can also be used to regulate the movement of rail cars as is done in the railway industry (Woldstad et al., 1995).

In a typical plant that generates power or processes materials, there are thousands of handwheels that are either motor operated or manually operated (Wieszczyk et al., 2009). Approximately 50% of the handwheels are manually operated (Shih et al., 1997), and in many cases, the torques required to actuate the handwheels exceed operators' capabilities. Parks and Schulze (1998) studied 336 valves of various handwheel diameters and heights at a large petroleum refinery and found that the cracking torque to open a handwheel ranged from 100 Nm to as high as 225 Nm; the "cracking torque" is defined as the torque required to start the initial movement of the handwheel from a locked position to an unlocked position (Amell and Kumar, 2001). Also, Jackson et al. (1992) measured the cracking torque of 217 valves in a chemical plant and found that 93% of the valves required torques over 400 Nm. A gross discrepancy results when comparing these torque values with operators' capabilities. Several studies measured maximum torque production capabilities of operators on handwheels of different sizes, heights, angles, and distances from operators (Wood et al., 1999/2000; Schulze et al., 1997). The maximum torque produced by the operators in these studies was approximately 62 Nm, which is significantly less than the torque demands in the field. In cases of high torque demands, more than one operator work together simultaneously in turning the handwheel using a valve wrench, which increases the lever arm length and improves the coupling factor (Figure 1) (Amell and Kumar, 2001).

Figure 1: Two operators work together in turning a handwheel (Amell and Kumar, 2001).

Moreover, even the maximum recommended torques in current guidelines approved by the Manufacturers Standardization Society of the Valve and Fittings Industry (MSSVFI) exceed operators' capabilities. Figure 2 is a graph that shows the relationship between recommended momentary forces and handwheel diameter (MSSVFI, 2009). The guidelines defines momentary force as follows: "if an operator must apply a high force to a manual actuator to cause a valve to break loose, but may exert relatively lower forces to continue actuation of the valve, the initial high force is referred to as momentary force" (p. 1). Based on the literature, the graph recommends momentary force values that are greater than the capabilities of operators. For instance, for a handwheel diameter of 46 cm, the peak momentary force of an operator is assumed to be 1,000 N. A 1000 N force acting on a 46 cm diameter handwheel is equivalent to a torque of 230 Nm. This torque is far greater than the maximum torque exerted by the operators in the literature (62 Nm) (Wood et al., 1999/2000; Schulze et al., 1997).

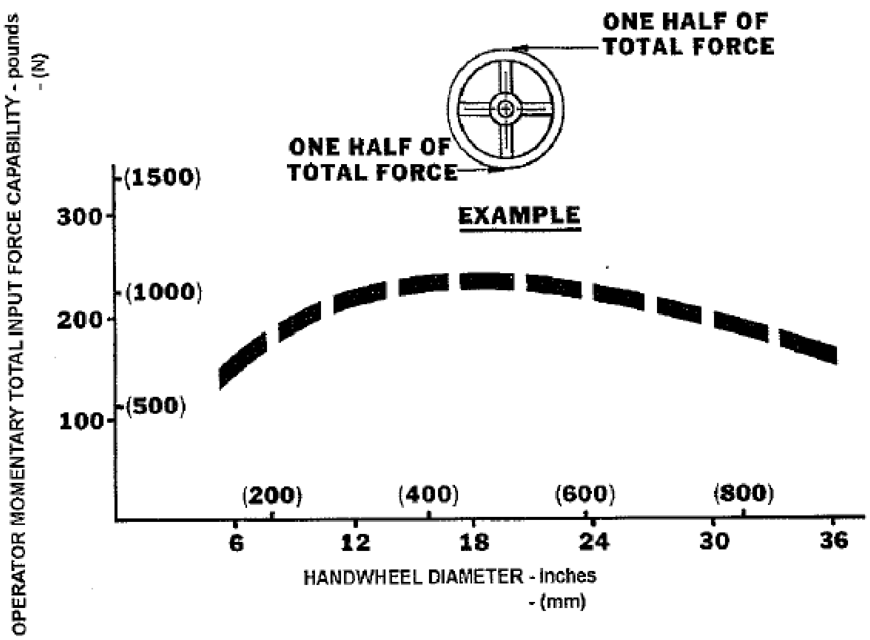


Figure 2: Operator momentary force capability as a function of valve wheel diameter (MSSVFI, 2009).

Since task demands exceed the physical capabilities of workers in handwheel actuation, it can be expected that injury rates in valve operations are high. Parks and Schulze (1998) conducted data searches for five downstream facilities of the Phillips Petroleum Company to determine the number of injuries experienced by operators over a three year period from 1993 to

1995. They also determined the number and percentage of injuries specifically associated with valve operations. Table 1 summarizes their results. About 57% of back injuries/discomfort and 75% of head, neck, and face injuries were associated with valve operations.

Table 1: Statistics on valve operation injuries (Parks and Schulze, 1998).

Category	Count
Number of Back Injuries Incurred by Operators	23
Number of Injuries Associated with Valve Operation	13 (56.52%)
Number of Injuries to the Head, Neck, and Face	4
Number of Injuries Associated with Valve Operation	3 (75%)

In relation to the back injuries, Johnson and Woldstad (1993) showed that valve operations place excessive compressive forces on the back. They developed an optimization-based biomechanical model of the handwheel turning task, and found that the compressive forces acting on the L3/L4 intervertebral disc level were about 1644 N for females and 6926 N for males. Such excessive forces can lead to severe back injuries and consequently place a substantial burden on the responsible organization. Back injuries are the most highly compensated injury type, accounting for nearly a third of all compensation dollars (Eccleston et al., 2007).

Amell (2000) administered musculoskeletal discomfort questionnaires to process operators at a large petroleum refinery to determine the percentage of operators that experience musculoskeletal discomfort from their jobs. The result indicates that 88% of the operators experienced musculoskeletal discomfort, and that the most physically demanding task for the operators was valve operations. In another study (Jackson et al., 1992; Amell and Kumar, 2001), the most physically demanding task at a chemical plant was cracking valves open.

Different factors contribute to the excessive task demands in valve-handwheel operations, such as: (1) the height of the handwheel from the standing surface; (2) the pitch angle or orientation of the handwheel (horizontal, vertical, or slanted); (3) the diameter of the handwheel; (4) the quality of the interface between the hands and the handwheel (handwheel rim shape or use of gloves); (5) the distance between the handwheel and operator, due to the presence of obstruction; (6) the high torque demands to crack a handwheel from a locked position to an unlocked position; (7) the continuous effort needed to fully open or close a valve (Amell and Kumar, 2001; Attwood et al., 2002).

The sixth factor, which deals with cracking torque demands, is primarily dependent upon a worker's strength. As mentioned earlier, the "cracking torque" is the torque required to start the initial movement of the handwheel from a locked position to an unlocked position, and it ends as soon as movement begins. This aspect of valve operations has been studied primarily through static strength experiments, where participants exert their maximal isometric torque on a stationary handwheel (Jackson et al., 1992). Schulze et al. (1997) and Wood et al. (1999/2000) also studied this aspect of valve operations (cracking handwheels) through isokinetic exertions.

The seventh factor, dealing with the continuous effort in handwheel actuation, has been primarily studied through dynamic strength experiments. It is more dependent on the worker's aerobic capacity and local muscular endurance (which is also correlated with strength). The measures of interest in these dynamic strength experiments are more focused on oxygen consumption and heart rate (Jackson et al., 1992).

1.1 Objectives

The objectives of this research were to:

1. Introduce an ergonomically-modified valve-wrench and compare it to conventional valve-opening methods, in terms of efficiency (time to open valve), perceived physical exertion (Borg-scale), and muscle loading of shoulder and trunk muscles,
2. Determine whether the torque setting (15 Nm and 30 Nm) of the valve affects the preferred valve-opening method,
3. Investigate operators' torque production capabilities and recommend maximum torque limits for different handwheel heights (knee, elbow, shoulder, and overhead levels) and angles (0^o, 45^o, and 90^o),
4. Determine an optimal handwheel height and angle, in terms of operators' maximum isometric torque exertions and muscle loading of shoulder and trunk muscles.

To meet these objectives, we conducted two separate projects. The first project was a dynamic strength experiment involving continuous handwheel actuation for evaluating the first two objectives. The second project was a static strength experiment involving maximal isometric torque exertions on a stationary handwheel. The latter project was used for evaluating the last two objectives.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter reviews studies that have investigated the effects of different characteristics or factors of handwheels (i.e. handwheel height, diameter, orientation, etc.) on valve operators. This review divided the literature into two main sections: (1) studies related to the initial handwheel actuation and (2) studies related to the continuous handwheel actuation. The first main section (Section 2.2) reviews studies dealing with the cracking torque that starts the initial movement of a handwheel from a locked position to an unlocked position. Each factor that affects valve operators in cracking handwheels open is discussed in a separate subsection. The second main section (Section 2.3) reviews studies dealing with the continuous effort of opening and/or closing handwheel-valve systems. Since there is a paucity of information concerning continuous handwheel actuation, this section is not divided into subsections.

2.2 Studies Related to the Initial Handwheel Actuation

Handwheel actuation has primarily been studied through isometric exertions on stationary handwheels. These studies simulate the cracking task that many operators have to go through when actuating a handwheel. Schulze et al. (1997) and Wood et al. (1999/2000) have studied this aspect of valve operations through isokinetic exertions. The measure of interest in the following studies is the maximum torque production of operators, and only one study also addresses the muscle activity of shoulder and trunk muscles. The purpose of these studies is to determine how different factors of handwheel-valve systems (i.e. handwheel height, diameter, orientation, etc.) affect operators' torque production and comfort, so that proper guidelines for valve operations can be developed. The following sections discuss each factor separately.

2.2.1 Effects of Handwheel Height on the Operator

In the field, handwheel heights range from lower than floor level to overhead level, where the handwheel may only be accessible through the use of a ladder or a platform (Wieszczyk et al., 2009). The height of the handwheel affects the posture of its operators, which may in turn affect their torque exertion capabilities and their comfort. There have been several studies that investigated the effects of height on maximum torque exertions, and their results are summarized in Table 2.

Table 2: Summary of maximum torque exertions (in Nm) on handwheels of various heights and angles in different studies.

Height	Wood et al. (1999/2000)	Wieszczyk et al. (2008)	Attwood et al. (2002)			Hoff (2000)	
	24 males and females	24 power plant mechanics or operators	57 process operators and managers			12 college students	
	90°	90°	0°	90°	45°	0°	90°
Overhead		153.3	111.8			36.48	72.37
Shoulder	47.59		143.3	152.9	130	70.07	74.51
Chest	46.76	138.9					
Waist	44.06		154.8	140.5		67.99	72.21
Middle of Thigh	46.64						
Knee	43.52	146.6	163.3	136.5	142.4	69.21	72.29
Floor						64.78	77.59

Parks and Schulze (1998) determined the cracking forces (or torques) required to actuate handwheel valves of different heights in an operating petrochemical process facility. Data were gathered for 336 handwheel valves with various diameters (ranging between 20.3 and 40.6 cm), heights, and orientations (vertical/horizontal). They considered nine different handwheel heights:

50.8 cm, 76.2 cm, 101.6 cm, 127.0 cm, 152.4 cm, 177.8 cm, 203.2 cm, 228.6 cm, and 250.4 cm (20 in, 30 in, 40 in, 50 in, 60 in, 70 in, 80 in, 90 in, and 100 in). Heights 228.6 cm and 50.8 cm required significantly more torque to crack (actuate) than the other heights (225 Nm and 174.42 Nm, respectively). None of the other handwheel heights were statistically significant from each other. Parks and Schulze (1998) concluded that handwheels that require high torques to actuate should be placed between 76.2 cm to 127 cm (30 in - 50 in) from the grade. From reviewing Parks' and Schulze's (1998) study, Amell and Kumar (2001) suggested that the most comfortable height for manual operations should be approximately between 76 cm and 177 cm because these heights required less torques (between 108.5 Nm and 146.36 Nm, respectively) than heights outside of that range. A limitation to this study, however, is that the pressure-level and the amount of friction in the threads between the different handwheel-valve systems differed. Valve systems with rusted threads, meaning more friction, and higher pressures tend to require more force to move the handwheel. Since these variables were not controlled, the results for the handwheel heights and angles may not be so reliable. These variables need to be controlled in future studies for more accurate results.

In a different study, Wood et al. (1999/2000) used similar height values as the previous study to determine how handwheel height affects torque production capability of operators. They considered five different heights: 50.8 cm, 76.2 cm, 102 cm, 127 cm, and 152 cm. These heights ranged between knee height and shoulder height of the participants. The handwheel had a diameter of 43.82 cm and was oriented vertically at all heights. The differences in mean torque production at the five heights were not statistically significant because participants were exerting nearly equivalent torques at all the heights. The mean torque output for each height was 43.52 Nm, 46.64 Nm, 44.06 Nm, 46.76 Nm, and 47.59 Nm, respectively. The difference between the maximum and lowest torque was only 4.07 Nm. The authors stated that since only heights between knee and shoulder levels were considered, the lack of significance between the handwheel heights should not be construed as alarming. The small sample size in their study (24 participants) may have affected the ability to detect a difference between heights (Amell and Kumar, 2001). Also, had they considered more heights, such as below the knee level and above the shoulder level, they predict that the torque outputs would have been significant.

Wieszczyk et al. (2009) evaluated the effects of overhead height, as well as chest height and knee height, on the maximum torque production of operators. In this study, an overhead posture was considered as a posture where the participant has the upper extremities raised with a shoulder flexion of 135^{o} and the hands gripping the handwheel at the 3 and 9 o'clock positions. The valve wheel in this study had a diameter of 45 cm and was vertically-oriented at all heights. The mean torque output was 146.6 Nm at knee height, 138.9 Nm at chest height, and 153.3 Nm at overhead height. Overhead height and chest height were significantly different from each other ($p = 0.02$). The participants exerted at least 10% greater torque at the overhead height than chest height. However, there were no significant differences in maximum torque between knee and chest heights and between knee and overhead heights. The authors recommended avoiding knee heights in valve system design because this height requires the operator to perform moderate to severe flexion of the trunk, which may lead to musculoskeletal disorders (MSD) at the low back. Chest heights or overhead heights were preferred over knee height. Although the torques at overhead height were higher than chest height, the authors still recommended placing handwheels at chest height since it is closer to the neutral posture; however, whether or not overhead height poses a greater risk of MSDs than chest height was not known. The authors did not base these recommendations on their experiment; rather, all of these recommendations were based on previous studies that were about the effects of posture on MSD development.

Wieszczyk et al. (2008) performed the same experiment as the above study, and they additionally evaluated the effects of handwheel height on the muscle activity of 8 trunk and shoulder muscles. Their study was one of the first studies to incorporate an electromyography (EMG) device to determine the biomechanical loading on the human body during valve operations. The eight muscles they considered were the left and right: pectoralis major, latissimus dorsi, erector spinae, and deltoid muscles. The three different heights they considered were knee, chest, and overhead height. They used a handwheel diameter of 45 cm and the valve wheel was vertically-oriented at all heights. The dependent variables were the maximum torque exertion and maximum voluntary contraction (%MVC) EMG. The statistical analysis and results for the maximum torque productions at the different heights were the same as the results in Wieszczyk et al.'s (2009) study. At overhead height, the authors found that the erector spinae was less active than the three shoulder muscles. However, at knee height, the erector spinae was the most active of all the muscles, which may be because knee height requires moderate to severe trunk flexion. The high muscle activity of the erector spinae supports Wieszczyk et al.'s (2009) recommendation that handwheel actuation at knee height is at higher risk of low back MSD. The authors also stated that at chest height, the erector spinae and latissimus dorsi were working optimally to generate torque. However, this statement was not based on the %MVC of the two muscles, but rather, through visual observations. In the contrary, the %MVCs for both muscles at chest height was higher than the %MVCs at overhead height and even knee height. However, the authors still conclude that handwheel valves should be placed near chest level because the arms and trunk are near neutral posture. From a general perspective, this is correct, but it would still need to be justified specifically for valve operations through EMG studies.

Attwood et al. (2002) collected data on the effects of different combinations of handwheel angles and heights on the maximum force production of operators. For a vertical handwheel orientation, they evaluated the effects of knee, waist, and shoulder height, and for a horizontal orientation, they evaluated the same heights, as well as overhead height. A total of 57 process operators and managers from two Exxon sites participated in the study. The participants performed isometric exertions on a handwheel with a diameter of 45.7 cm (18 in). Their results are summarized in Table 3. Height/angle orientations with similar letters in the "Equivalence" column of Table 3 mean that the mean torque outputs are not significantly different. For each angle (vertical and horizontal), the heights were significantly different from each other, except for the case of waist height and knee height at the vertical orientation; they were not significantly different from each other.

Table 3: The mean maximum force/torque production of operators at different handwheel orientations (Attwood et al., 2002).

Angle	Height	Force (N)	Torque (Nm)	Equivalence				
Horizontal	Overhead	489.3	111.8	A				
	Shoulder	627.1	143.3			C		
	Waist	677.3	154.8				D	
	Knee	714.7	163.3					E
Vertical	Shoulder	668.9	152.9				D	
	Waist	614.7	140.5			C		
	Knee	597.3	136.5		B	C		

Interestingly, at the vertical handwheel orientation, height and mean maximum torque production have a positive relationship, but in the horizontal orientation, height and torque have an inverse relationship. At the horizontal orientation, the mean maximum torque production was highest at knee height (163.3 Nm), and at the vertical orientation, the shoulder height resulted with the highest torque (152.9 Nm). This depicts that not only height should be a factor in handwheel design, but also the orientation (pitch angle) of the handwheel valve should also be considered.

Hoff's (2000) study is one of the most comprehensive studies related to handwheel actuation in the literature. She considered combinations of five different heights and three different angles and assessed their interactions. The results showed that the height effect, angle effect, and their interaction were significant, each with a p-value of 0.0001. Table 4 summarizes the mean maximum torque production of the operators at the different handwheel heights and angles. The maximum torque produced in the horizontal orientation was at shoulder level, and the maximum torque produced in the vertical orientation was at floor level. Similar to Attwood et al.'s (2002) study, this depicts that the appropriate height of a handwheel depends on the orientation of the handwheel. A limitation to this study, however, was that it used only 12 participants.

Table 4: The mean maximum torque production of operators at different handwheel heights and angles (Hoff, 2000).

Mean Torque (Nm)		
	Horizontal	Vertical
Overhead	36.48	72.37
Shoulder	70.07	74.51
Waist	67.99	72.21
Knee	69.21	72.29
Floor	64.78	77.59

2.2.2 Effects of Handwheel Pitch Angle on the Operator

The pitch angle of a handwheel is another factor that may affect torque production capabilities of operators. Valve wheels with pitch angles of 0^o (horizontal orientation), 45^o, and 90^o (vertical orientation) are frequently found in the field. The handwheel angle can affect wrist and arm kinematics during valve operation, which may in turn affect torque production capabilities and pose risk for MSD development. Unfortunately, there is a limited amount of research that directly deal with the effects of pitch angle of handwheels on the operator. Only three papers were found in the literature that deal with pitch angle. Two of them are discussed in this section, and the third paper, which is related to the continuous effort of valve operations, is discussed in Section 2.3. Table 2 above summarizes the effects of handwheel angle and height on maximum torque exertion from different studies.

Schulze et al. (1997) measured the maximum torque production capability of 12 participants for a vertically and horizontally oriented handwheel. The torque differences between the two orientations were minimal and not significant. Schulze et al. (1997) also studied the effects of handwheel height and diameter on torque production; however, they did not provide any torque data for the combination of wheel diameter, height, and angle.

Attwood et al.'s (2002) study, on the other hand, did provide maximal torque data for different combinations of handwheel angles and heights. A total of 57 process operators and managers from two Exxon sites participated in their study. The participants performed isometric exertions on a handwheel with a diameter of 45.7 cm (18 in) at a total of 9 different orientations. The study evaluated 4 different heights: knee, waist, shoulder, and overhead. At knee height and shoulder height, pitch angles of 0^o (horizontal), 45^o, and 90^o (vertical) were considered; at waist height, only 0^o and 90^o angles were considered; and at overhead height, only 0^o angles were considered. Since overhead height tested only a horizontal handwheel orientation, the effects of angles at overhead height were not determined.

One of the results that was already mentioned earlier from observing Table 3 was that the handwheel orientation affects the relationship between handwheel height and the mean maximum torque production of operators. At the vertical handwheel orientation, height and maximum torque seem to have a positive relationship, but in the horizontal orientation, height and torque seem to have an inverse relationship.

More results are summarized in Table 5. Table 5 is similar to Table 3, except that the rows were rearranged and sorted based on height level, rather than handwheel angle. Also, the 45^{o} orientation was added to Table 5. Height/angle orientations with similar letters in the "Equivalence" column of Table 5 mean that the mean torque outputs are not significantly different. At each height, the pitch angles were significantly different from each other, except for the case at knee height. At knee height, the vertical orientation and 45^{o} orientation were not significantly different from each other.

The pitch angle that produces the highest torque depends on the height of the handwheel valve. For instance, at shoulder height, the vertical orientation had the highest torque output (152.9 Nm). However, at waist height and knee height, the vertical orientation actually had the lowest torque output (140.5 Nm and 136.5 Nm, respectively), and the horizontal orientation had the highest torque output (154.8 Nm and 163.3 Nm, respectively). So at shoulder height, a vertically oriented handwheel would be recommended, but at waist height and knee height, a horizontally oriented handwheel would be recommended. This conclusion is based on the ergonomic principle that a person is at lower risk of injuries when working at lower percentages of their maximum strength. However, these recommendations should be further evaluated and justified through electromyography studies to determine the biomechanical loading on the human body at the different height and angle orientations.

Table 5: The mean maximum force/torque production of operators at different handwheel orientations (Attwood et al., 2002).

Height	Handwheel Orientation	Force (N)	Torque (Nm)	Equivalence				
Overhead	Horizontal	489.3	111.8	A				
Shoulder	Vertical	668.9	152.9				D	
	45 degrees	568.9	130.0		B			
	Horizontal	627.1	143.3			C		
Waist	Vertical	614.7	140.5			C		
	Horizontal	677.3	154.8				D	
Knee	Vertical	597.3	136.5		B	C		
	45 degrees	623.1	142.4			C		
	Horizontal	714.7	163.3					E

Hoff's (2000) study found that the horizontal and vertical handwheel orientations were significantly different from each other with a p-value of 0.0001. The mean maximum torque production at the different handwheel angles and heights is summarized in Table 4. An interesting finding from this study is that the vertically oriented wheel always resulted in a higher maximum torque. However, that was not the case in Attwood et al.'s (2002) study. Hence, more research on the effect of pitch angle is still needed before making any recommendations.

2.2.3 Effects of Handwheel Diameter on the Operator

The handwheel diameter is another factor that can affect the maximum torque production of operators. This can be proven through basic knowledge in physics. The torque created on a handwheel is equal to the tangential (rim) force applied on the handwheel times the radius of the handwheel (Torque = Force * Radius). From this equation, it could generally be understood that larger handwheels produce higher torques.

Schulze et al. (1997) measured the maximum torque production capability of 12 participants for four different wheel sizes (40.6 cm, 22.9 cm, 20.3 cm, and 17.8 cm). The handwheel was horizontally-oriented at a height of 81 cm. The main effects of wheel size were statistically significant. The post hoc tests revealed that the largest wheel produced the greatest torque (62 Nm) of the four wheels. The medium wheel produced significantly larger forces than the smaller wheels and significantly less forces than the larger wheel. However, no significant difference existed between the two smallest wheels (17.8 cm and 20.3 cm). These results support the general idea that larger diameters produce greater torques.

Another study by Parks and Schulze (1998) measured the cracking torque required to actuate 336 handwheel valves at an operating petrochemical process facility. Five different handwheel diameters were found at the facility, which were 20.32 cm, 25.40 cm, 30.48 cm, 35.56 cm, and 40.64 cm. The main effects of the handwheel size were significant ($p < 0.0003$). Handwheel valves with larger diameters required higher torques to actuate. This was because the larger handwheels had larger valves and higher pressures in their valves, which required more force to move.

2.2.4 Effects of Distance on Operators

Another factor that may affect maximum torque production is the distance between the operator and the handwheel. In the field, there may be obstructions that get in the way of actuation, limiting the movement of the operator and possibly creating a distance between the operator and the handwheel. This may in turn affect the torque production capability of the operator.

Wood et al. (1999/2000) addressed the topic of distance between the operator and handwheel. They only evaluated two distances from the handwheel, which were derived from anthropometric data published by the National Aeronautics and Space Administration (NASA). The derived minimum and maximum distances were 37.34 cm and 52.58 cm, respectively. The handwheel in this study had a diameter of 43.82 cm and was vertically oriented. The participants produced a significantly higher torque at 37.34 cm (48.16 Nm) than at 52.58 cm (43.28 Nm). Although the difference between the two distances was small (about 15 cm), the results still indicate that at a greater distance from the handwheel, an operator is likely to produce a lower torque.

2.2.5 Effects of Handwheel Rim Design on Operators

A study by Woldstad et al. (1995) found that grip strength is highly correlated with maximum handwheel turning strength. The correlation coefficient between them was 0.80. Since grip strength seemed to play a major role in wheel turning strength, McMulkin and Woldstad (1995) designed three new handwheels that would likely improve handwheel grip and then tested whether these new designs are better than the standard wheel design, in terms of maximum torque production. All four wheel designs had a diameter of 28 cm. The only difference between them was the structure and design of the rim. The standard wheel they used was one that is most commonly used for railroad hand brakes. The rim diameter (not wheel diameter) for the standard wheel is 2.8 cm. The second wheel design had a larger rim diameter of 4.3 cm, and its rim surface was knurled for better grip. The third wheel design had a smaller rim diameter of 2.5 cm but additionally had spheres attached to the rim. The spheres were 6.5 cm in diameter and were also partially knurled to facilitate grip. The fourth wheel design had a zigzag structure that followed a circular pattern, which formed the wheel. This wheel was also knurled and had a diameter of 4.3 cm. A total of 24 college students (12 male and 12 female) participated in the study and were asked to perform one-handed isometric exertions on all four handwheel designs. The torque generated by the participants was highest for the fourth wheel design (zigzag) followed by the third wheel design, then the second wheel design, and finally, the standard wheel design. The average torque values for each handwheel design were 156 Nm, 118 Nm, 106 Nm, and 101 Nm, respectively. All the new designs, which were ergonomically designed to facilitate grip, produced higher torques than the standard wheel. The larger rim diameter increased the contact area between the hand and handwheel, which facilitated a better grip and in turn increased torque production. Also, the knurled surface and zigzag designed handwheel improved grip, which also resulted to higher torques.

2.3 Studies Related to the Continuous Effort in Valve Operations

The continuous effort in valve operation begins immediately after cracking the valve from a locked position. It involves the continuous effort of turning the handwheel to a closed or open position, which can take as long as 15 minutes (Jackson et al., 1992). The variables of interest in this area would be more dependent upon worker's aerobic capacity and local muscular endurance, which is correlated with strength (Jackson et al., 1992). About 5 to 15 minutes of continuous handwheel actuation may be more physically and physiologically demanding than the initial cracking torque, even though the torque during continuous handwheel actuation is less than the cracking torque (Jackson et al., 1992). This is because continuous handwheel actuation requires continuous muscular effort at high torques for a period of time. Although continuous handwheel actuation is more demanding, there is much less research in this area than the initial handwheel actuation. Only three papers were found in the literature concerning the continuous effort in valve operations.

The first paper (Jackson et al., 1992) examined the role of endurance in continuous handwheel actuation. To develop a proper valve handwheel simulator, Jackson et al. (1992) first measured the total work required to open and close 188 valves in a chemical plant and then simulated a handwheel-valve system based on the results. Fifty one college students participated in the study to perform 15 minutes of continuous handwheel actuation at a rate of 15 revolutions per minute (rpm) and a fixed power output of approximately 1916.4 Nm/min. Only 19 of the 51 participants (37%) were able to complete the 15 minute test. Of the remaining 32 participants, 20 stopped before even completing four minutes of the test, due to fatigue. These results demonstrate that valve operations in the field demand more from operators than what they can endure.

The second paper (Meyer et al., 2000) evaluated the physiological strain of large handwheel actuation. The variables of interest in this study were heart rate, oxygen consumption, and subjective evaluation using the Borg scale. The experiment had a total of three handwheel configurations: (1) horizontally-oriented handwheel at elbow height; (2) vertically-oriented handwheel at elbow height; and (3) horizontally-oriented handwheel at 70 cm from the floor. Also, two torque settings were used, which were 20 Nm and 35 Nm. Eight male workers participated in the study, where they had to rotate a 40 cm diameter handwheel at a rate of 33 rpm for a 2 minute period. The handwheel configuration had no significant effect on the heart rate. Also, the subjective ratings did not differ significantly between the three wheel positions. However, oxygen consumption was significantly lower at the vertical orientation than the other two horizontal orientations. For the 35 Nm torque setting, the mean heart rate, oxygen consumption, and rating of perceive exertion were 149.7 beats per minute (bpm), 1.86 min^{-1}, and 14.7, respectively. For the 25 Nm torque setting, the mean heart rate, oxygen consumption, and rating of perceived exertion were 130.4 bpm, 1.48 min^{-1}, and 11.3, respectively. The cardio-respiratory strains demonstrate that the work in the high-torque configurations can be considered hard because most of the participants were working close to their maximum work capacities (Max HR = 220 – Age; Minnesota code, 1967). However, in contrast, the perceived exertions were surprisingly low. This misperception can create a risk for operators because they may perceive their exertion to be low and continue to operate without proper rest; when in reality, they are performing physiologically demanding tasks to the extent where their heart rate and oxygen consumption may be close to their maximum level. The researchers concluded that the position of the handwheel had small effect on physiological strain and that the standard torque values (ranging between 120 Nm to 200 Nm; DIN, 1986; CEN, 1998) for handwheel actuation are too high, based on the results of this study. Table 6 summarizes the results and limitations of different studies related to the effects of height and angle of large handwheels on operators.

Another study conducted by Aghazadeh et al. (2012) investigated the effects of four different opening methods on Borg-ratings, efficiency, and the muscle loading of upper extremity and trunk muscles. They compared a modified valve wrench to conventional valve-opening methods, which included using bare hands, a conventional wrench with obstructions in the way limiting handwheel actuation (CW-restricted), and a conventional wrench with no obstructions in the way (CW-unrestricted). All methods were performed at 25 Nm and 50 Nm, during which EMG measurements were recorded from the right and left biceps, right and left medial deltoids, right and left trapezii, and right latissimus dorsi muscles. Also, the time to fully open the valve using each method was recorded. After each trial, participants were asked to rate their perceived physical exertions on a Borg-scale. They concluded the modified wrench to be the optimal technique to use for a 25 Nm torque, in that it was the most efficient and perceived to be the least

Table 6: Summary of studies related to the effects of height and angle of large handwheels on operators.

	Schulze et al. (1997)	**Wood et al. (1999/2000)**	**Hoff (2000)**	**Meyer et al. (2000)**	**Attwood et al. (2002)**	**Wieszczyk et al. (2008)**
Heights	3 heights Height effect significant - but post-hoc tests showed them to be equal.	5 heights (knee to shoulder) Height effect NOT significant - The difference b/w max and min torque was small (4.07 Nm). A positive relationship between height and torque -Highest torque at shoulder -Lowest torque at knee	5 heights (knee to overhead) Height effect significant No noticeable trend across heights at either angle - Floor height had highest torque when angle 90^o - Shoulder height had highest torque when angle 0^o	2 heights (elbow and 70 cm from floor level) at 0^o Borg-ratings and heart rate were not significant for height Oxygen consumption was significantly lower at elbow level than at 70 cm (approximately at mid-thigh).	5 heights (knee to overhead) Height main effects significant -inverse relationship with torque when angle 0^o (Highest torque at knee) -positive relationship with torque when angle 90^o (Highest torque at shoulder)	3 heights (knee to overhead) Height main effect significant. No noticeable torque trend across heights EMG activities of trunk muscles were highest at chest height
Angles	Used 2 angles (0^o and 90^o) Angle effect NOT significant	Used only 90^o angle	Used 3 angles (0^o, 90^o, and sideways) Angle effect significant (as well as height-angle interaction effect) 90^o generated higher torques than 0^o at all heights.	Used 2 angles (0^o and 90^o) at elbow height Borg-ratings and heart rate were not significant for angle Oxygen consumption significantly lower at 90^o than at 0^o	Used 0^o, 90^o, and 45^o angles Angle effect significant at waist and shoulder height, but not knee height. Angle affects relationship b/w height & torque. - At 90^o, height and torque have positive relationship - At 0^o, height and torque have inverse relationship.	Used only 90^o angle
Limitations	Results of main effect tests and post hoc tests did not match. Had a sample size of 12 (less than Wood et al.'s, 1999/2000 study). Did not use EMG	Did not consider overhead height Used only one angle (90^o) Small sample size (n = 24) may have affected ability to detect significant difference (Amell and Kumar, 2001) Did not use EMG	Had a sample size of 12, which is less than what was used in Wood et al.'s (1999/2000) study. Heights levels were fixed measures and not with respect to participant's anthropometry. Did not use EMG	Not every height had every angle Considered only 2 heights and 2 angles. Did not use EMG	Not every height had every angle (e.g. overhead had only one angle and waist had two angles). Height levels were fixed measures and not with respect to participant's anthropometry Used 3 different knee heights depending on angle Did not use EMG	Used only one angle (90^o) Used a sample size of 24 similar to Wood et al. (1999/2000) EMG results suggested back muscles work hardest at chest height. Need additional study to confirm results.

strenuous. Also, the EMG results showed it to be one of the least physically demanding techniques at this torque. However, at 50 Nm, the modified wrench was associated with the highest overall muscle activity and was perceived to be the most strenuous method. So, although the modified wrench was the best method to use at 25 Nm torque, their results indicated that it should be avoided at higher torques. The participants commented that the modified wrench was uncomfortable due to the friction between the hand and the handle while rotating the handwheel. The authors recommended adding a sleeve or a rotating handle to the modified wrench for future testing. This recommendation along with other modifications to the wrench is further discussed in the following Rationale Section.

CHAPTER 3: RATIONALE

A review of the literature concerning valve operations in the field shows that torque demands for handwheel actuation exceed the capabilities of operators. Also, process operators have described valve operations to be the most physically demanding task in their work place (Jackson et al., 1992; Amell, 2000). Johnson and Woldstad (1993) developed an optimization-based biomechanical model of the handwheel turning task and found that the forces acting on the back were about 1644 N for females and 6926 N for males. Such excessive forces are potential risks for severe back injuries. Another study showed that 57% of process operators associated their back injuries with handwheel operations (Parks and Schulze, 1998). Back injuries are the most highly compensated injury type, accounting for nearly a third of all compensation dollars (Eccleston et al., 2007). The average total incurred costs per claim to the lower and upper back are $17,738 and $11,533, respectively (Itasca, 2004). Hence, it is necessary to develop more operator-friendly valve systems to eliminate or reduce the prevalence of back injuries. To assist this development, there needs to be proper guidelines that industries can follow. Currently, the guidelines set by the MSSVFI (2009) recommend torques that have far exceeded operators' capabilities. All the above information suggests that more research is needed to develop handwheel-valve systems that match operators' physical capabilities

Previous studies attempted to determine the optimal height of handwheels based on data of operators' maximum torque exertion. However, the findings of these studies were mixed. Some studies found no significant effect of height, while others did. The lack of detecting a significant effect in the former studies may have been due to the small sample size chosen (i.e. 24 participants) or because not enough height levels were evaluated (Wieszczyk et al., 2009; Wood et al., 1999/2000); only heights between shoulder and knee level were evaluated. Hence, this research included more participants of both genders and overhead height in the experiments. Even the studies that did detect a significant effect of height still had mixed results. The maximum torque was sometimes found to be at shoulder, floor, overhead, and knee level (Wieszczyk et al., 2009; Hoff, 2000; Attwood et al., 2002). This indicates that maximum torque data is not sufficient alone to determine the optimal height. This research additionally used EMG data of various trunk and upper extremity muscles for determining the optimal height. Although there already is an EMG study in the literature that evaluates handwheel heights, its results seemed contradictory to general expectations (Wieszczyk et al., 2008). Their results showed that chest height produced more trunk muscle activity than overhead height and even knee height. This result would seem to suggest that an operator would be safer to work at overhead height or knee height than at chest height, although chest height is closest to neutral posture. To determine whether this is true, this research incorporated EMG in the experiments and also evaluated more heights. Moreover, rather than using fixed heights, this research used heights with respect to participants' anthropometry. This is believed to be a more appropriate investigation of handwheel heights. For instance, consider a fixed height of 152 cm; this level may be the shoulder level of an average person, yet the elbow level of a tall person. The height difference of the two participants may have an effect on the data. To eliminate this confounding effect, this research used handwheel heights with respect to participants' anthropometry.

Since this study used a larger sample size of participants, the maximum torque exertions of the participants were used as a guide for determining a maximum recommended torque for handwheel-valve systems. One principle of ergonomics is to design for the extreme of the population to ensure that most of the population is accommodated. Equipment that requires the application of force should be designed for the weakest segment of the population so most of the users are able to use the equipment. The weakest segment in the process industry is the 5^{th} percentile of female operators (Attwood et al., 2002). Therefore, this study used a large sample of participants with an equal number of males and females.

The effect of handwheel angle on torque production has been addressed in the literature but not to a degree of satisfaction because results are mixed among studies. Some studies found no significant effect of handwheel angle, while others did. Since more research is needed on angle effects, this research evaluated three handwheel angles (0^o, 45^o, and 90^o), using maximum torque data, as well as EMG data. This research also assessed the interaction effects of height and angle.

Due to the high torque demands in the field, valve operators are forced to use wrenches for turning handwheels. Since wrench-use is prevalent in valve operations, wrenches need to be ergonomically designed for the user to reduce the risk of injury and improve efficiency. There has never been any study that investigated current designs of wrenches or attempted to determine a more convenient design for operators. This research introduced an ergonomically-modified wrench and compared it to conventional valve-opening methods, in terms of efficiency, perceived exertion, and muscle activity of shoulder and trunk muscles.

Furthermore, most of the research related to valve operations focused only on maximum isometric torque exertions, while the dynamic aspect of handwheel actuation has been much ignored. Only three studies were found in the literature that investigated the continuous effort in valve operations, even though continuous handwheel actuation may be more physically and physiologically demanding than the initial cracking torque (Jackson et al., 1992). Aghazadeh et al. (2012) developed a modified wrench and compared it to conventional valve opening methods in continuous handwheel actuation. They recommended adding a sleeve to the handle of the wrench, which would eliminate the discomfort and friction created between the operator's hand and the tool while turning the handwheel. The current research sought to incorporate this recommendation to the modified wrench along with other modifications, including increasing the diameter of the handle to maximize perceived comfort (Kong and Lowe, 2005) and increasing the handle length to accommodate the hand breadth of the 95th percentile of the population (NASA, 1978). Since valve wrenches are a commonly used tool in industries, it is vital to develop an ergonomic design of valve wrenches through systematic research. Therefore, this research seeks to build on the efforts of Aghazadeh et al. (2012) in the development of an ergonomic valve wrench.

PROJECT-1: COMPARISON OF FOUR VALVE-OPENING METHODS AT TWO TORQUE SETTINGS

CHAPTER 4: PROJECT-1 METHODS

Project-1 compared four different valve-opening methods in continuous handwheel actuation. One of the opening methods involved using an ergonomically modified valve-wrench, while the remaining three methods were conventional valve-opening methods. All methods were performed at two different torque settings, 15 Nm and 30 Nm, to determine whether torque has an effect on the overall preferred method. Comparisons were made in terms of the time to open the valve, perceived physical exertion (Borg-ratings), and muscle activities of shoulder and trunk muscles.

In addition, this project compared accepted reference contraction (RC) procedures (also known as maximum voluntary contraction) in the literature for the anterior deltoid and trapezius muscles to newly proposed RC procedures. The RC exercises in the literature have become accepted as a standard only by their wide use. However, systematic research identifying the RC exercises that produce the true maximum contraction levels of these muscles is still needed.

4.1 Participants

Fifteen male participants in good health between the ages of 18 and 30 were tested. A power analysis was performed to determine whether the sample size had sufficient power to detect differences in the means. According to Cohen (1988), the minimum suggested power for an ordinary study is 80%. In using fifteen participants, the analysis resulted in a power of at least 81%, which satisfies the minimum requirement. More detail on the power analysis is provided in Appendix A.

Table 7 summarizes the demographic information of the participants. The average age, height, and weight of the participants were 23.4 years, 179.8 cm and 81.1 kg, respectively. The participants were primarily graduate or undergraduate students of Louisiana State University (LSU).

Table 7: Participants' demographic information in dynamic strength project.

15 Males	Avg (S.D.)	Range
Age (year)	23.4 (3.1)	18 - 30
Height (cm)	179.8 (5.1)	173-191
Weight (kg)	81.1 (12.1)	59-109

The Physical Activity Readiness Questionnaire (PAR-Q, British Columbia Ministry of Health) was used to screen participants for cardiac and other health problems, such as dizziness, chest pain, or heart trouble (Appendix B). Any participant who answered yes to any of the questions on the PAR-Q was excluded. The age, weight, and height of each participant was measured and recorded. Prior to the data collection, the experimental procedures and the demands of the testing were explained to the participants and their signatures were obtained on informed consent forms approved by the LSU institutional review board (IRB) (Appendix C).

4.2 Tools and Equipment

4.2.1 Handwheel-Valve System

A handwheel-valve system was used for this study. The handwheel-valve system consists of a standard 15 cm (inside diameter) manual gate valve and a 36 cm diameter handwheel. The handwheel is horizontally-oriented at a height of about 100 cm from the grade (Figure 3). To fully open this valve system from a closed position, it requires approximately 18 counterclockwise handwheel revolutions.

Figure 3: A 15 cm manual gate valve with a 36 cm diameter handwheel.

4.2.2 Valve Wrenches

In this study, two types of wrenches for handwheel actuation were used: (1) a conventional wrench and (2) a modified wrench. The conventional wrench is a forged aluminum "crow's foot" valve wheel wrench. Its handle is approximately 28 cm long as depicted in Figure 4. The modified wrench (Figure 5) is similar in design, except that it is modified to have a handle that can bend anywhere between 0 and 180 degrees. This was done by fabricating a hinge in the handle 17 cm from the crow's foot. Since this design has a shorter handle than the conventional wrench, obstructions (i.e. pipes, tanks, walls, etc.) during handwheel actuation is not as much of a problem for it. It allows the operator to turn a handwheel continuously without having to unhook the wrench. The handle diameter and length were also modified to meet ergonomic designs. Kong and Lowe (2005) evaluated the relationships between the diameter of cylindrical aluminum handles and perceived comfort. They found that the optimal handle diameter in maximizing subjective comfort was 19.7% of the user's hand length. Based on the average hand length size of their male participants, they recommended a handle diameter of approximately 3.76 cm. Hence, a handle diameter of 3.76 cm was selected for this study. Also, the handle for the modified wrench was lengthened to be larger than the hand breadth of the 95th percentile U.S. Air Force pilots (9.6 cm) (NASA, 1978). An additional ~1.5 cm was provided at both ends of the handle as clearance to prevent the operator's hand from getting pinched by the handle. So the total length of the handle was increased to 12.5 cm. Furthermore, the handle was modified to include a sleeve, which allows the sleeve to spin on its axis. This addition eliminates the friction between the operator's hand and the handle during handwheel actuation.

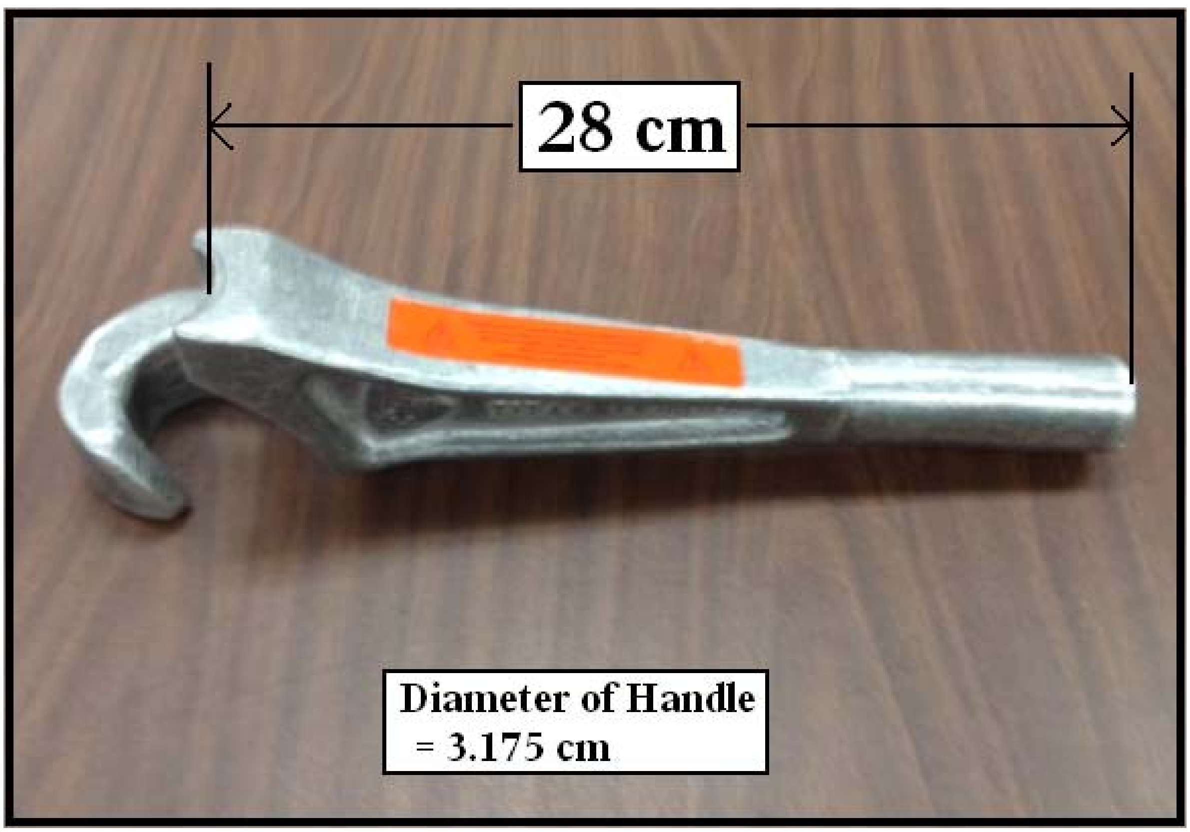


Figure 4: Dimensions of conventional valve wheel wrench.

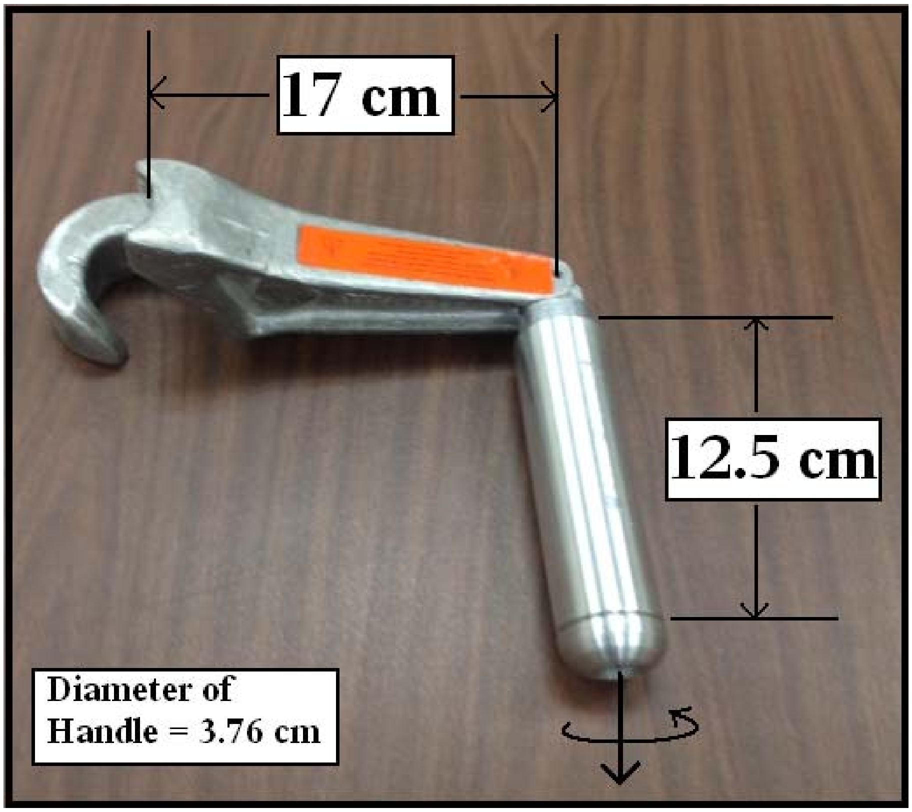


Figure 5: Dimensions of modified valve wheel wrench.

4.2.3 Electromyography (EMG) System

This study used an eight channel wireless electromyography (EMG) system to measure the electrical activity of shoulder and trunk muscles (Delsys Inc., Boston, USA). The EMG system consists of a Myomonitor IV, an input module, eight surface electrodes, and one reference electrode. The input module consists of eight channels for the surface electrode connections and an additional channel for the reference electrode connection. The input module acquires the EMG signals from the surface electrodes and transmits the signals to the Myomonitor IV. The Myomonitor IV records the EMG signal either as a wireless transmitter or an autonomous data logger. This study used the wireless transmitter mode to collect data. In this mode, EMG data is transmitted over a wireless local area network (WLAN) to the host computer for real-time display and storage.

The surface electrodes that were used for EMG signal acquisition are parallel bar active surface electrodes (DE-2.3 EMG Sensors, Delsys Inc., Boston, USA). They are single differential with CMRR of 92 dB and input impedance greater than $10^{15}\Omega$. The sensor contacts are made from 99.9% pure silver bars, measuring 10 mm in length, 1 mm in diameter, and spaced 10 mm apart. Figure 6 shows the Myomonitor wireless EMG system that this study used, including a close up shot of a surface electrode and its dimensions.

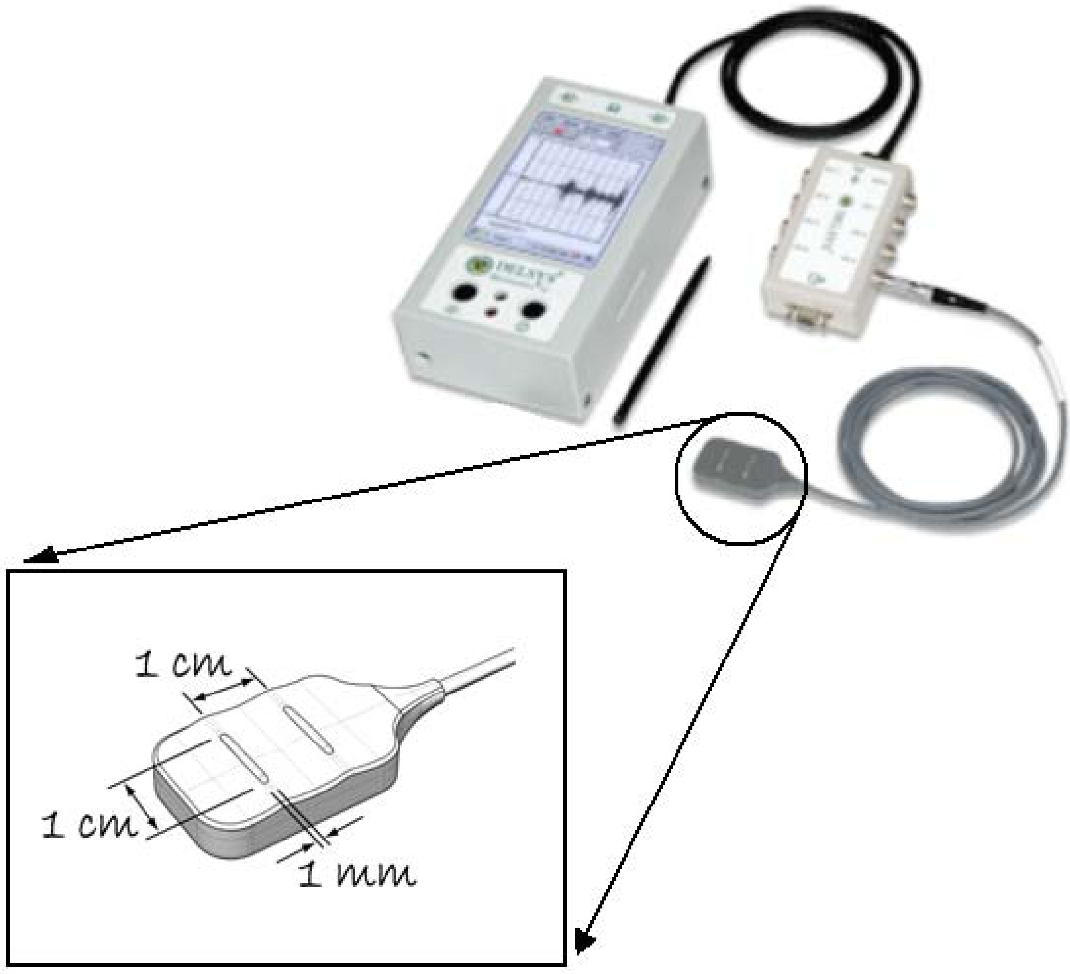


Figure 6: Myomonitor wireless EMG system.

4.2.4 Borg's Scale

The Borg CR-10 (category ratio) scale was used for subjective evaluations of exertion of the valve opening tasks (Appendix D) (Borg, 1970; Borg, 1982; Noble et al., 1983). The scale ranges from "nothing at all" to " very very difficult." A 0 means that there is "no exertion at all" involved with the physical exercise. A 10 means "very very difficult," indicating that the exercise is the strongest physical task ever experienced. An exertion falling between the two extremes is rated with any number between 0 and 10. The description of the ratings are given in Figure 7. For instance, a 1 rating indicates a "very light" exertion, and a 5 rating indicates a "difficult" exertion. Perceived exertion using a Borg scale has been proven useful in estimating the actual intensities of exertions (Chen et al., 2002).

Rating of Perceived Exertion
10 point scale

0 - Nothing at all
1 - Very light
2 - Fairly light
3 - Moderate
4 - Some what difficult .
5 - difficult
6
7 - Very difficult
8
9
10 - Very, very difficult

Figure 7: Borg's category-ratio based CR10 scale (Borg, 1970; Borg, 1982; Noble et al., 1983).

4.3 Experimental Task

Participants were asked to continuously actuate a handwheel valve from fully open to fully closed, using four different techniques. The four methods of actuation are:

1. Bare hands (BH): This method required participants to repetitively actuate the handwheel using their hands only. The actuation involved gripping and turning the handwheel repetitively. Each actuation began with the right hand supine at approximately the 6 o'clock position and the left hand prone at approximately the 12 o'clock position. The maximal length of each actuation was limited to half a revolution.
2. Conventional wrench unrestricted (CW-U): In this method, the conventional wrench was used to actuate the handwheel with no restrictions or limitations to how far the wheel could be turned. Participants were required to keep both hands at the end of the wrench, as they continuously turned the wheel all the way around. This technique simulated a handwheel-valve system that has no obstructions that would limit movement during handwheel actuation.
3. Conventional wrench restricted (CW-R): Similarly, this method used the conventional wrench to turn the handwheel, but it assumed that there were obstructions getting in the way of actuation and limiting the amount of turning. Hence, the maximal length of each actuation was limited to 2/3rd of a turn. Participants were required to keep both hands at the end of the wrench during actuation.
4. Modified wrench (MW): This method used the modified wrench to actuate the handwheel. Participants were required to keep both hands at the end of the wrench, as they continuously turned the wheel all the way around.

All techniques were performed at two different torque settings, 15 Nm (11.06 ft-lb) and 30 Nm (22.13 ft-lb). Initially, a 50 Nm torque was going to be considered because it is approximately equivalent to the maximal recommended torque for a 36 cm (14 in) diameter handwheel (MSSVFI, 2009). However, through preliminary observations, it was noticed that the 50 Nm torque was too high for dynamic continuous handwheel actuations, especially when using the wrenches. To maintain the dynamic nature of the experiment, a 30 Nm torque was used as the upper torque. At this torque level, volunteers in the preliminary tests were able to continuously turn the handwheel, without any stops or pauses during actuation. Also, this study investigated a second torque for determining the torque effects on each technique, in terms of the time to fully open the valve, perceived physical exertion, and muscle loading. The second torque was half of the higher torque, which was 15 Nm.

4.4 Experimental Design

A two factor split-plot experimental design was used. Participants served as blocks within which experimental conditions were randomized. The independent variables were method (BH, CW-R, CW-U, and MW) and torque setting (15 Nm and 30 Nm). Each participant performed a total of 8 (4 methods × 2 torques) trials. The eight trials were divided into two sets of four trials, and torque was randomized to the sets. The methods were randomized to the trials within each set or torque. Torque served as the whole-plot treatment and method as the sub-plot treatment. Figure 8 illustrates an example of how the experimental design was applied to the trials. Each small square represents a trial, and each column represents a set of four trials. For each participant, first, the two torques are randomized to the columns (sets), and then the four methods are randomized to the four squares (trials) within each column. The dependent variables of this study were the perceived exertion ratings, the time to complete each trial, and the maximum normalized EMG activities of the right and left anterior deltoids, right and left trapezii, right and left latissimi dorsi, and right and left erector spinae muscles.

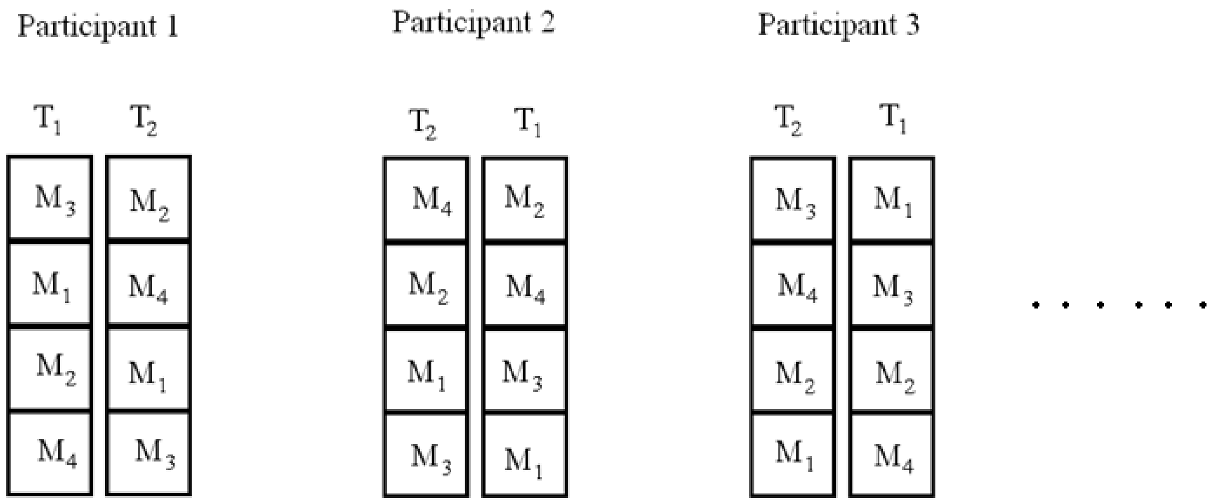


Figure 8: Split-plot design where participants served as blocks, torque (T) as the whole plot treatment, and method (M) as the sub-plot treatment.

The means model was as follows:

$$y_{Tr} = \mu_{T,M} + \rho_P + \omega_S + \varepsilon_{Tr} \quad (1)$$

Where:

- y_{Tr}: is the response or dependent variable that was measured in each trial (Tr), which in this study represents either the time it took to open the valve, Borg-rating, or normalized EMG activity of any one muscle (i.e. right anterior deltoid, left anterior deltoid, right trapezius, left trapezius, right latissimus dorsi, left latissimus dorsi, right erector spinae, or left erector spinae);
- $\mu_{T,M}$: is the fixed effect term due to torque (T) and method (M), representing the population average;
- ρ_P: is a random term due to participant (P);

- ω_S: is a random term due to set of trials (S);
- ε_{Tr}: is a random term due to trial (Tr).

4.5 Research Hypotheses

For each dependent variable (i.e. the time to open the valve, Borg-ratings, and normalized EMG activity of each of the eight muscles investigated), the following hypotheses were tested:

- Hypothesis 1 for Method Main Effect
    - H_0: The means of all the valve-opening methods are equal.
    - H_1: The mean of at least one valve-opening method is significantly different than the remaining means.
- Hypothesis 2 for Torque Main Effect
    - H_0: The means are equal between both torque settings (15 Nm and 30 Nm).
    - H_1: The means between both torque settings are significantly different than each other.
- Hypothesis 3 for Method and Torque Interaction Effect
    - H_0: There is no significant interaction between the method and torque effects.
    - H_1: There is a significant interaction between the method and torque effects.

4.6 Data Collection and Processing

4.6.1 Orientation

Each participant was given an orientation, introducing them to the equipment, data collection procedures, and specifics of the experimental tasks. After the orientation, they were asked to sign the IRB form. Following that, demographic information (age, height, weight, and gender) of the participants were collected and recorded. Then the participants underwent a five-minute warm-up session on a treadmill (Nautilus T914 Commercial Series, Nautilus, Inc. Global Headquarters

16400 SE Nautilus Drive Vancouver, WA 98683). The speed of the treadmill was adjusted by the participants to their comfortable walking speed (3 miles per hour).

4.6.2 EMG Preparation

Subsequent to the warm-up session, preparations were carried out to get the participants ready for EMG data acquisition. Any hair on the skin at the right and left anterior deltoids, right and left trapezii, right and left latissimi dorsi, and right and left erector spinae muscles were removed. Removing hair improves adhesion, especially for sweaty skin during dynamic exertions. Also, the same areas were cleaned with alcohol for electrode placement. The purpose of cleaning the skin is to get rid of dead skin cells, dirt, and sweat. After cleaning the skin, the EMG surface electrodes were attached to the muscles of interest. Changing the location of the electrode over the muscle belly can drastically change the amplitude and various spectral variables of the EMG signal. Therefore, it was very important to accurately position the electrode on the muscle belly, which results in the best EMG signal. A sub-optimal electrode placement can result in misleading results and errors in the data. This study used the following electrode locations for the muscles of interest:

- Anterior Deltoids – participant supine with arm at side, placed electrode three fingerbreadths below the anterior margin of the acromion (Perotto et al., 1994).
- Trapezii – With participants' arms resting at their sides, placed electrode along the line joining the acromion and the spinous process of the seventh cervical vertebra (C7), at one-third the distance from the lateral edge of the acromion (Farina et al., 2002).
- Latissimi dorsi – participant prone with arm at side and palm up, placed electrode three fingerbreadths distal to and along posterior axillary fold (Perotto et al., 1994).

- Erector Spinae – participant prone, placed electrode on lumbar erector spinae region at approximately 3 cm lateral to the L3-4 vertebrae interspace (McGill, 1992; Lamoth et al., 2006; Van der Hulst et al., 2010). Since the L3-L4 interspace is approximately at the same level of the iliac crest, the iliac crest was identified first in locating the L3-4 interspace (Chakraverty et al., 2007; Pysyk et al., 2010).
- Ground electrode – placed on the participant's clavicle (Soderberg and Knutson, 2000).

Figure 9 shows a general illustration of how to properly position an electrode on a muscle. The arrow label on the electrode must be parallel to the muscle fibers of the muscle of interest. Figure 10 illustrates the exact positioning and location of the electrodes for each muscle in this study. After attaching the electrodes, participants performed a test contraction for each muscle pair to ensure good electrode-skin contact.

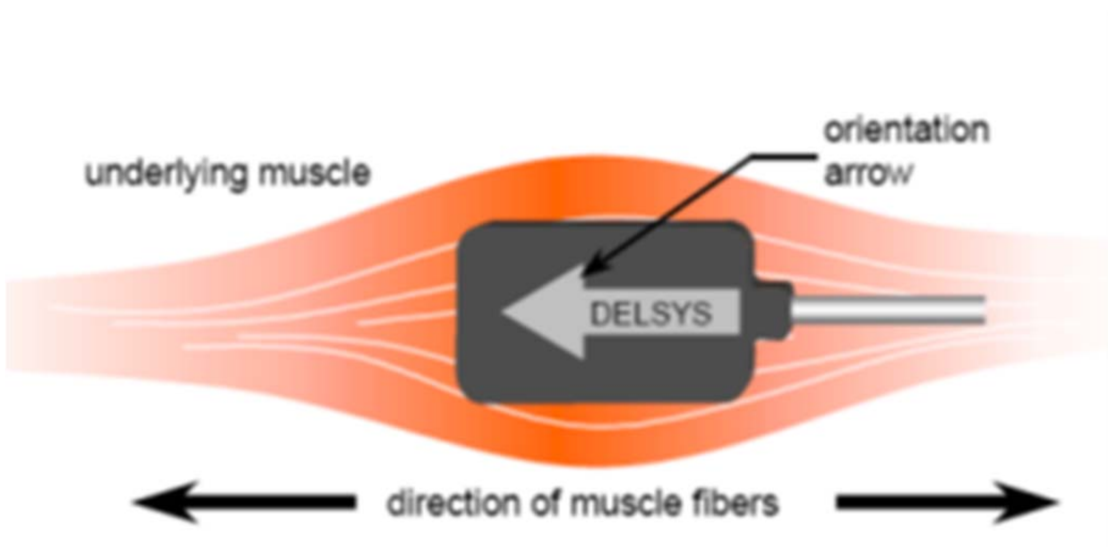


Figure 9: The arrow label on the electrode must be parallel to the muscle fibers for an optimal signal.

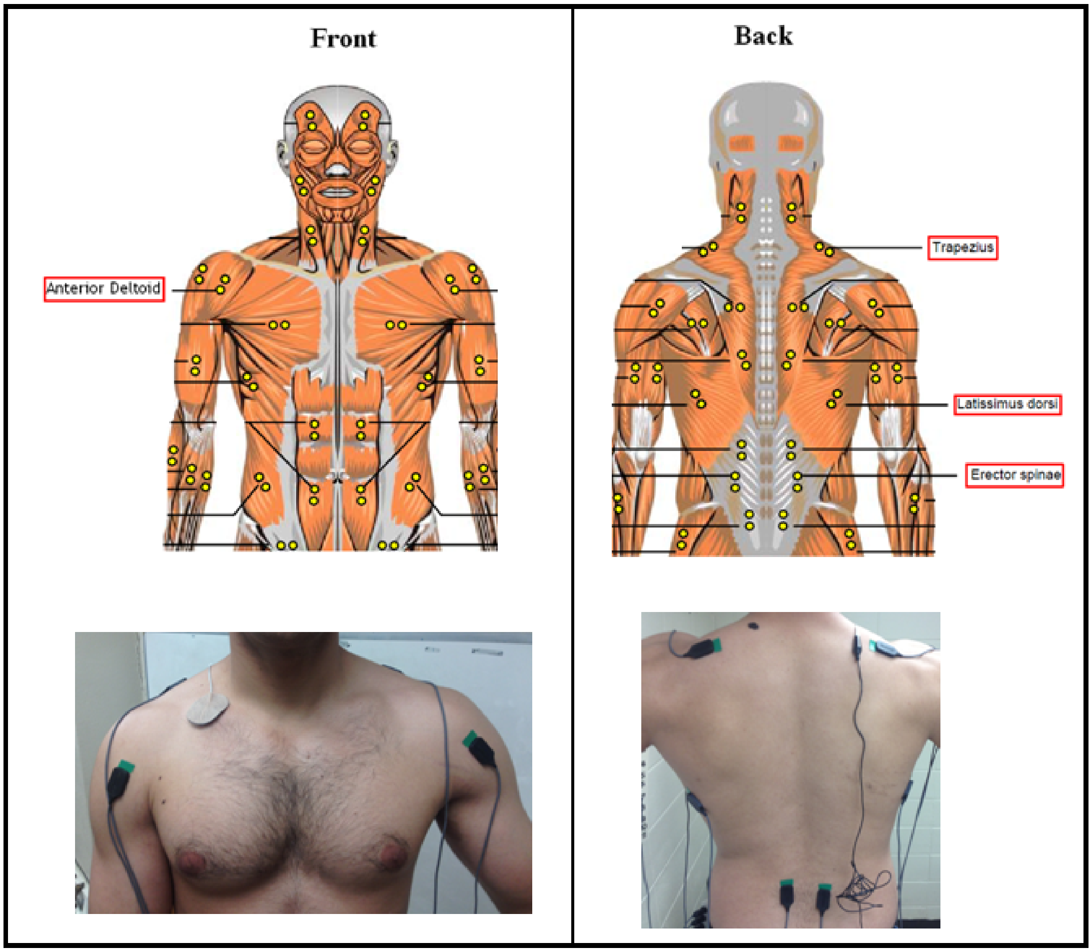


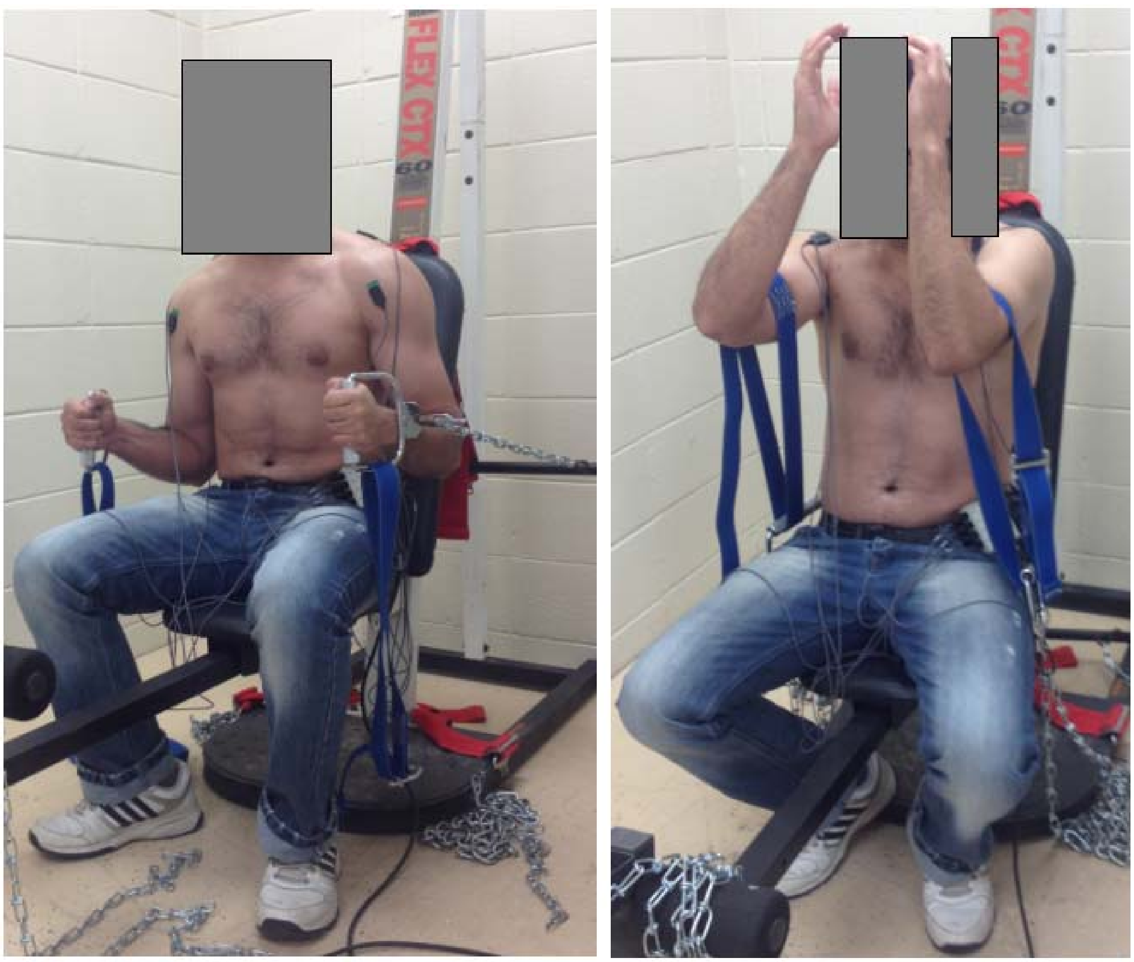
Figure 10: The exact location and positioning of each electrode for the anterior deltoid, trapezius, latissimus dorsi, and erector spinae (Konrad, 2005).

4.6.3 RC Exertions

Comparison of EMG between and within participants required normalizing the EMG data. To do this, participants first performed a series of reference contraction (RC) exertions. The RC exertions were performed for each investigated muscle separately. Each RC exertion sought to isolate its corresponding muscle in a maximum isometric exertion against a static resistance. The maximum EMG activities in the RC exertions were used for normalizing the EMG data collected in the experimental trials. The procedure for each RC exertion is listed below:

- Anterior Deltoids RC – The literature suggests that the RC (also known as maximum voluntary contraction or MVC) for the anterior deltoid is attained through maximum isometric shoulder flexion against a static resistance, while the shoulder is at 0^{o} and elbow at 90^{o} (Cordasco et al., 1996; Hintermeister et al., 2010; Konrad, 2005) (Figure 11a). However, through preliminary testing, this research found that the anterior deltoid can produce even higher EMG activities through positioning the shoulder at 90^{o} flexion rather than 0^{o}. To validate the new proposed RC exertion, participants performed both RC exertions. However, to maintain consistency in the data processing, only the proposed RC exertion was used to normalize the data. Figure 11b illustrates the arm positioning in the proposed RC exertion. Fixed straps were hung over the distal end of the upper arm as a static resistance. Participants then performed maximum isometric shoulder flexion against the fixed straps.
- Trapezii RC – The literature suggests that the RC for the trapezius is attained through maximum isometric shrugs (shoulder at 0^{o} abduction; Figure 12a) or lateral raises (shoulder at 90^{o} abduction) against a static resistance (Konrad, 2005, Andersen et al., 2008). However, through preliminary testing, this research observed that the highest EMG activities for the trapezii muscles were attained during maximum isometric lateral raises at approximately 100^{o} of shoulder abduction. Participants performed both RC exertions, but only the proposed RC exertion was used in processing the data. Figure 12b illustrates the arm positioning in the proposed RC exertion, in which participants performed lateral raises against fixed chains.

- Latissimi dorsi RC – With shoulders abducted at 30^{o} and elbows flexed 90^{o}, participants performed extension and internal rotation against fixed chains (Hintermeister et al., 1998; Dark et al., 2007) bringing their shoulder blades together (Figure 13).
- Erector Spinae RC – In the prone laying position with the lower extremities stabilized and upper extremities off the ground, participants performed trunk extension to approximately end range against manual resistance at the upper thoracic area (Figure 14) (Kendall et al., 2005).



(a) (b)

Figure 11: Reference contraction for anterior deltoid muscles according to: (a) the literature and (b) the proposed method.

(a) (b)

Figure 12: Reference contraction for trapezius muscles according to: (a) the literature and (b) the proposed method.

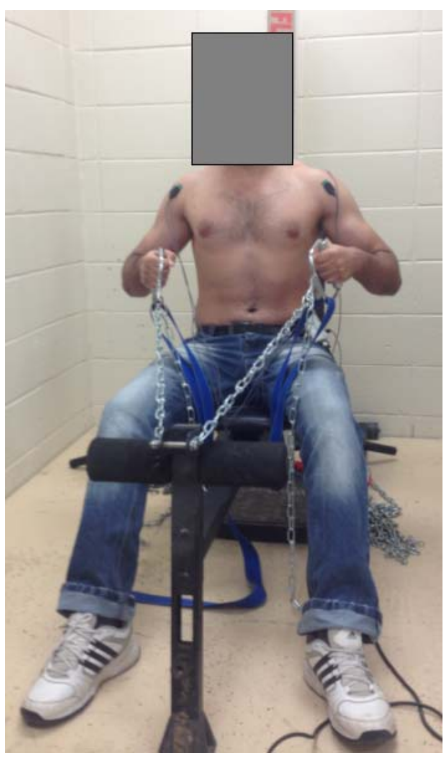


Figure 13: Reference contraction for latissimus dorsi muscles.

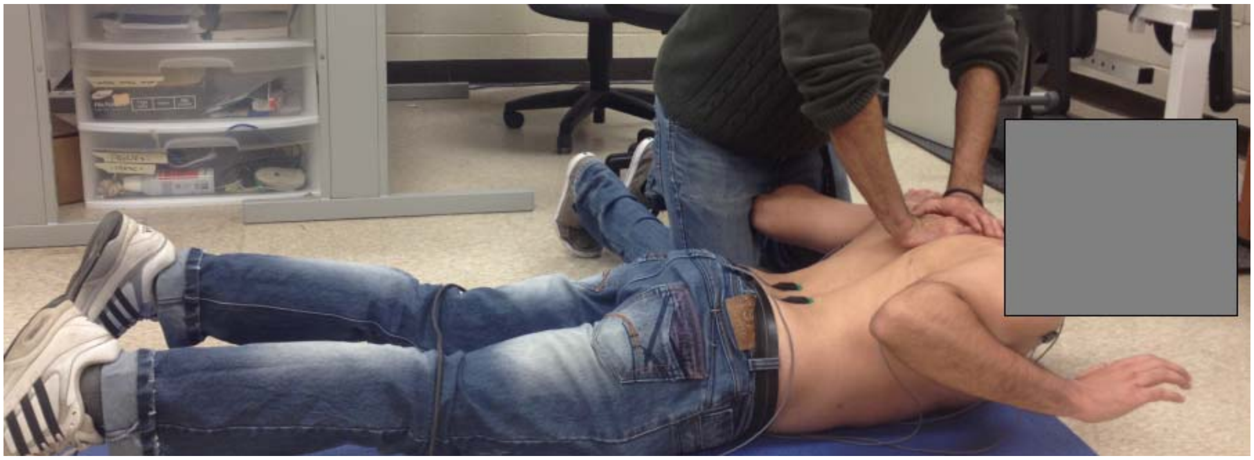


Figure 14: Reference contraction for erector spinae muscles.

For the RC exertions, participants were asked to gradually exert to their maximum effort in 3 to 5 seconds, hold it for 3 seconds, and gradually decrease the force in 3 seconds (Konrad, 2005). Each RC exertion was repeated three times. To avoid muscular fatigue, repetitions were separated with 30 to 60 seconds of rest (Konrad, 2005) and RC sets were separated with 2 minutes of rest (Caldwell et al., 1974; Sparto et al., 1997; Hummel et al., 2005; Andersen et al., 2008). The maximum EMG activity of the three repetitions was used for normalizing the EMG data. During RC exertions, EMG data was collected for a period of 15 seconds, giving participants enough time to reach their maximum exertion.

4.6.4 Experimental Trials

After the RC exertions, the participants actuated a handwheel-valve system from fully closed to fully open (counterclockwise). Since this project is concerned with continuous handwheel actuation and not the initial cracking force, the wheel was cracked open 1/3rd of a revolution for each participant before they began. Participants actuated the handwheel using four different methods at two different torques (The experimental task was discussed more in detail in Section

4.3). Hence, there were a total of 8 trials, and the trial order was randomized. Participants were given at least three minutes of rest between trials. De Salles et al. (2009) reviewed the literature on rest periods in strength training, and concluded that three to five minutes of rest between sets are safer psychologically and physiologically than shorter periods of rest. Moreover, they found that three to five minutes of rest allowed for greater repetitions and higher levels of muscular power over multiple sets. If requested, participants were provided with more time to rest until they felt ready for the next trial.

Before each trial, participants were trained and given time to practice the technique (i.e. bare hands, conventional wrench restricted, conventional wrench unrestricted, or modified wrench) until comfortable. They were instructed to use only their upper body in actuating the wheel. Feet had to be kept firm on the ground at approximately shoulder length apart. In the techniques that used a wrench (modified wrench or conventional wrench), the participant stood with the left foot in front of the right foot in order to maintain balance during handwheel actuation and also to provide space for the wrench to move freely between the wheel and the participant's torso. In the bare hands technique, reaching around the wheel was not required and consequently balance was not affected much. Therefore, in this technique, the feet were aligned at approximately shoulder length apart. Also, participants were allowed to stand at a distance from the wheel that they felt most comfortable with. However, once they determined their comfortable distance, they had to maintain that position and limit their foot movement as much as possible. These limitations were made to ensure that the participants used only their upper body in actuating the wheel. All the techniques had to be performed as fast as possible to simulate "real world" conditions where valves must be opened and/or closed quickly. Such situations occur during emergency conditions and in starting up and shutting down a unit.

EMG activity was recorded from the right and left anterior deltoids, trapezii, latissimi dorsi, and erector spinae muscles. The EMG data acquisition started approximately 3 seconds into each trial and lasted for 20 seconds. The raw EMG activity from each electrode location was demeaned first and then full-wave rectified. The full wave rectified EMG activity was then low pass filtered at 4 Hz, using a fourth-order dual pass Butterworth digital filter, to form a linear envelope (Burnett et al., 2007). The peak activation of each muscle in each trial was normalized with respect to the maximum EMG activity of its corresponding RC exertion. Thus, results for each muscle were reported as a percentage of the muscle's RC (%RC).

The task of fully opening the valve system from the closed position was timed for each trial using a stopwatch. The time measurements were used to compare the efficiency of the different opening techniques (Appendix D).

Immediately after each trial, participants were required to rate their perceived exertion on a Borg CR-10 scale (Appendix D). All the participants were given a brief introduction on the Borg scale and an explanation on how to use it. Participants were directed to always start by looking at the verbal expressions and then choose the corresponding number. For instance, if they perceived the opening task to be "difficult," then they would rate the task as 5, and if they perceived it to be "very light," then they would rate it as 1. They were instructed to base their ratings solely on how they personally perceived the exertion to be without considering the thoughts of others.

4.7 Statistical Analysis

A two-sample t-test was used for comparing the mean maximum EMG activity of each muscle between the RC method in the literature and the proposed RC method. Also, a two factor split-plot analysis of variance (ANOVA) was used to assess the effects of the different opening techniques and torque-settings on the normalized EMG activities, Borg-ratings, and times. A post hoc analysis, in the form of Tukey multiple pairwise comparisons (Honestly Significant Difference [HSD]), was performed. A significance level (α) of 5% was used for all cases. Statistical significance was based on calculated p-values.

CHAPTER 5: PROJECT-1 RESULTS

5.1 RC Results

This study compared accepted RC methods in the literature for the anterior deltoid and trapezius muscles to newly proposed RC methods. Eight participants were involved in this part of the project. The average age, height, and weight of the participants were 23.9 year, 177.8 cm, and 77.8 kg, respectively (Table 8). The data for the individual participants are provided in Appendix F.

Table 8: The demographic information of the participants involved in the RC comparison tests.

8 Males	Avg (S.D.)	Range
Age (year)	23.9 (3.0)	18 - 28
Height (cm)	177.8 (3.3)	172.7 - 182.9
Weight (kg)	77.8 (9.0)	59.1 - 86.4

Figure 15 presents the EMG results in a bar graph for the right and left anterior deltoids using both RC methods. The EMG activity of the right anterior deltoid using the accepted RC method in the literature was 0.33 mV (S.D. = 0.15 mV) versus 0.52 mV (S.D. = 0.12 mV) of the proposed RC method. The proposed RC method significantly increased the EMG activity of the right anterior deltoid by an average of 58% from the accepted RC method ($p = 0.0144$). Similarly, an increase in EMG activity was noticed in the left anterior deltoid using the proposed RC method. The EMG activity in the left deltoid increased from 0.29 mV (S.D. = 0.17 mV) to 0.43 mV (S.D. = 0.07 mV) using the proposed method, which is approximately a 46% increase from the accepted RC method. Although a substantial increase was noticed, the t-test did not detect the difference as significant. The p-value for this test was 0.0633, which was slightly greater than the significance level of 0.05. The lack of statistical significance may be a result of the low number of participants involved in this part of the experiment. In conclusion, the proposed RC method appears to be a more accurate representation of the true maximum contraction level of the anterior deltoids than the accepted RC methods.

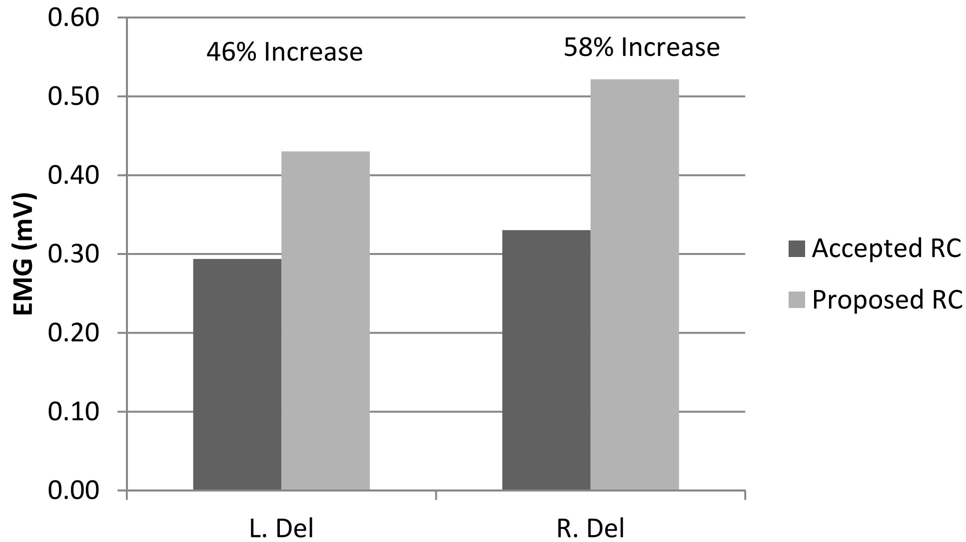


Figure 15: The average maximum EMG activities from the right and left anterior deltoids using the accepted RC method in the literature (accepted RC) and the proposed RC method in this study (proposed RC).

Also, the accepted RC method in the literature for the trapezii muscles was compared to a newly proposed RC method, which involves isometric lateral raises at approximately 100^{o} shoulder abduction. Figure 16 illustrates the average maximum EMG activities of the right and left trapezii muscles using the accepted RC method and proposed RC method. As before, the EMG activity using the proposed RC method was significantly higher than the accepted RC method. The proposed method significantly increased the EMG activity of the left and right trapezii by an average of 68% from the accepted RC method (p-values equaled 0.0116 and 0.0447, respectively). The average maximum EMG activity of the right trapezius using the accepted RC method was 0.45 mV (S.D. = 0.20 mV), in comparison to 0.76 mV (S.D. = 0.22 mV) using the proposed RC method. The average maximum EMG activity of the left trapezius muscle using the accepted RC method was 0.43 mV (S.D. = 0.20 mV) versus 0.72 mV (S.D. = 0.32 mV) of the proposed RC method. These results show that the proposed RC method provides a more accurate EMG activity of the true maximum contraction level of the trapezii muscles than the accepted RC method in the literature. Therefore, the maximum EMG activities from the proposed RC methods were used for normalizing the EMG data in this research. The SAS program and results for the t-test are provided in Appendices G and H, respectively.

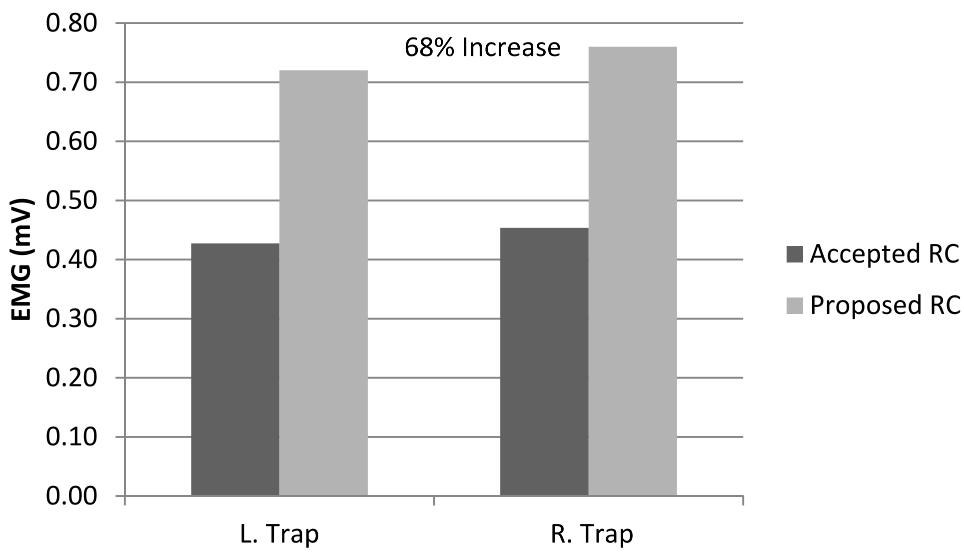


Figure 16: The average maximum EMG activities from the right and left trapezii muscles using the accepted RC method in the literature (accepted RC) and the proposed RC method in this study (proposed RC).

5.2 Time to Open Valve

The times to fully open a valve using four different methods – bare hands (BH), conventional wrench-restricted (CW-R), conventional wrench-unrestricted (CW-U), and modified wrench (MW) – were measured at 15 Nm and 30 Nm. Table 9 presents the average times and standard deviations associated with each valve-opening method at each torque. At 15 Nm, MW required the least time to fully open the valve (20.7 s), followed by CW-U (22.3 s), BH (34.2 s), and finally CW-R (86.4 s). A similar trend was found at 30 Nm, where MW was associated with the least time (25.4 s), followed by CW-U (28.8 s), BH (45.4 s), and CW-R (90.6 s). For all methods, the average times required to open the valve was greater at 30 Nm than at 15 Nm. From 15 Nm to 30 Nm, the average times increased by 11.2 s for BH, 4.3 s for CW-R, 6.4 s for CW-U, and 4.7 s for MW.

Table 9: The average time and standard deviation associated with each valve-opening method at 15 Nm and 30 Nm.

Torque	Method	Time (sec)	
		Average	S.D.
15 Nm	BH	34.2	9.2
	CW-R	86.4	21.6
	CW-U	22.3	4.8
	MW	20.7	3.6
30 Nm	BH	45.4	22.4
	CW-R	90.6	24.5
	CW-U	28.8	8.9
	MW	25.4	7.4

Figure 17 presents a graph of the average times associated with the different method-torque combinations. The trends across methods for both torques are almost parallel, suggesting the interaction effect between method and torque is not significant. Table 10 presents the ANOVA results for the time variable and shows that the interaction effect to be in fact not significant with a p-value of 0.6954. This result indicates that the method and torque effects are independent of each other and can be interpreted separately.

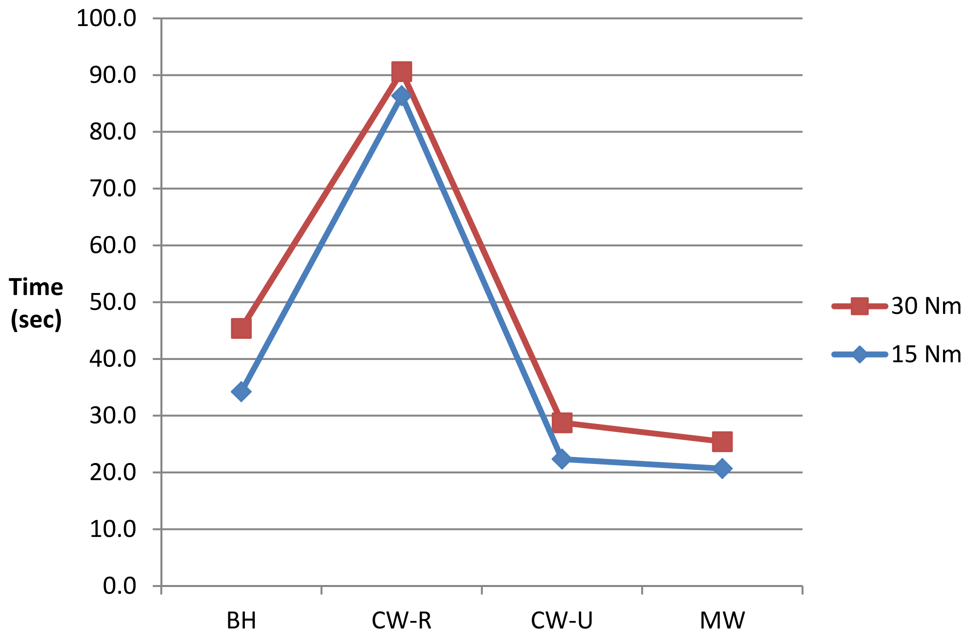


Figure 17: The average times required to fully open the valve using the different methods at 15 Nm and 30 Nm.

Table 10: ANOVA results for the average times to open the valve for the torque (T) and method (M) main effects and their interaction effect (T*M). A highlighted p-value indicates that the corresponding effect is significant.

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
T	1	98	8.61	0.0042
M	3	98	180.47	<.0001
T*M	3	98	0.48	0.6954

To examine the method main effect, the average times of each method were averaged over both torques. Table 11 presents these averages and their associated standard deviations. The average times were, from lowest to highest, 23.1 s for MW, 25.6 s for CW-U, 39.8 s for BH, and 88.5 s for CW-R. Figure 18 illustrates these time averages and shows the trend across methods.

Table 11: The overall average time and standard deviation associated with each valve-opening method.

Method	Time (sec)	
	Average	S.D.
BH	39.8	17.1
CW-R	88.5	23.1
CW-U	25.6	7.1
MW	23.1	5.8

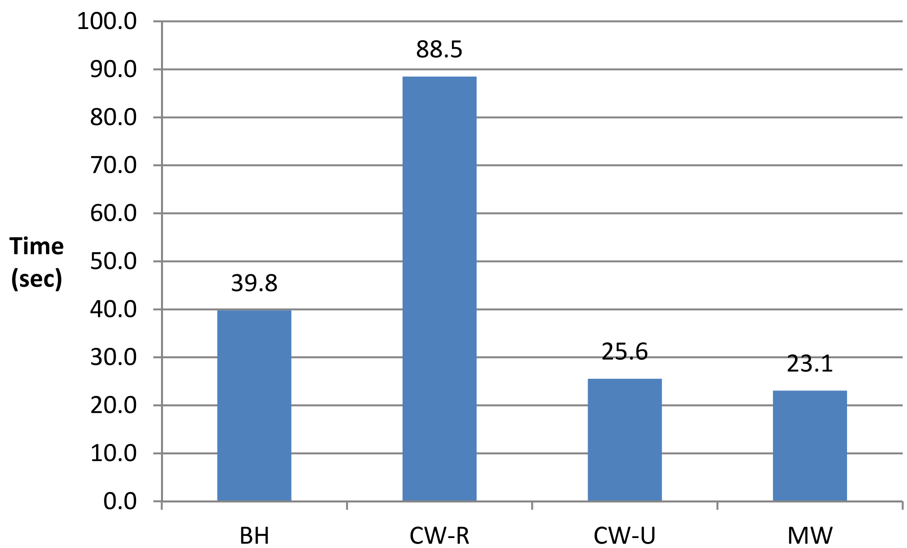


Figure 18: A bar graph of the average times associated with each valve-opening method averaged over 15 Nm and 30 Nm.

Unlike the interaction effect, the method main effect was statistically significant with a p-value less than 0.0001 (Table 10). This result indicates that at least one method is significantly different than the remaining methods, in terms of the average time to fully open the valve. The Tukey test was performed to identify the specific methods that were statistically different from the other methods. Table 12 presents the Tukey results for the time variable, grouping methods into different letter groups. Methods that fall under the same letter group are not significantly different in average times; whereas, methods in different letter groups indicate that their average times are significantly different. CW-U and MW were the only methods that shared the same letter group, meaning that their average times were not significantly different from each other. These two methods differed only by 2.5 s. All other pairwise comparisons between methods were significantly different from each other.

Table 12: Tukey-Kramer output for the average times of the method main effect.

M	**Estimate**	**Letter Group**		
CW-R	88.5	A		
BH	39.8		B	
CW-U	25.6			C
MW	23.1			C

The overall average time to fully open the valve at the higher torque was greater than the overall average time at the lower torque. At 30 Nm, the average time of all methods was 47.5 s, while at 15 Nm, the overall average time was 40.9 s (Table 13). This difference was found to be statistically significant with a p-value of 0.0042 (Table 10).

Table 13: The overall average times and standard deviations associated with 15 Nm and 30 Nm.

Torque	Time (sec)	
	Average	S.D.
15 Nm	40.9	12.1
30 Nm	47.5	17.6

5.3 Borg-Ratings Associated with Opening-Methods and Torques

After each opening-method, participants were asked to rate their perceived exertions on the Borg CR-10 scale. Table 14 presents the average Borg-ratings and standard deviations associated with each valve-opening method at each torque. At 15 Nm, MW was perceived to be the least strenuous method (2.1), followed by CW-U (2.6), BH (3.6), and finally CW-R (3.7). At 30 Nm, MW was associated with the least Borg-rating (3.9), followed by CW-U (4.5), CW-R (5.1), and BH (6.1). For all methods, the average perceived exertions were greater at 30 Nm than at 15 Nm. From 15 Nm to 30 Nm, the average Borg ratings increased by 2.4 for BH, 1.4 for CW-R, 1.9 for CW-U, and 1.8 for MW.

Table 14: The average Borg-rating and standard deviation associated with each valve-opening method at 15 Nm and 30 Nm.

Torque	Method	Borg-Rating	
		Average	S.D.
15 Nm	BH	3.6	2.1
	CW-R	3.7	2.2
	CW-U	2.6	1.3
	MW	2.1	1.0
30 Nm	BH	6.1	2.0
	CW-R	5.1	2.0
	CW-U	4.5	1.6
	MW	3.9	1.8

Figure 19 presents a graph of the average Borg-ratings of the different method-torque combinations. The trends of the Borg-ratings across methods for both torques are almost parallel, suggesting the interaction effect between method and torque is not significant. The ANOVA test did not yield a significant interaction effect between torque and method, which had a p-value of 0.4501 (Table 15). This result indicates that the method and torque effects are independent of each other and can be interpreted separately.

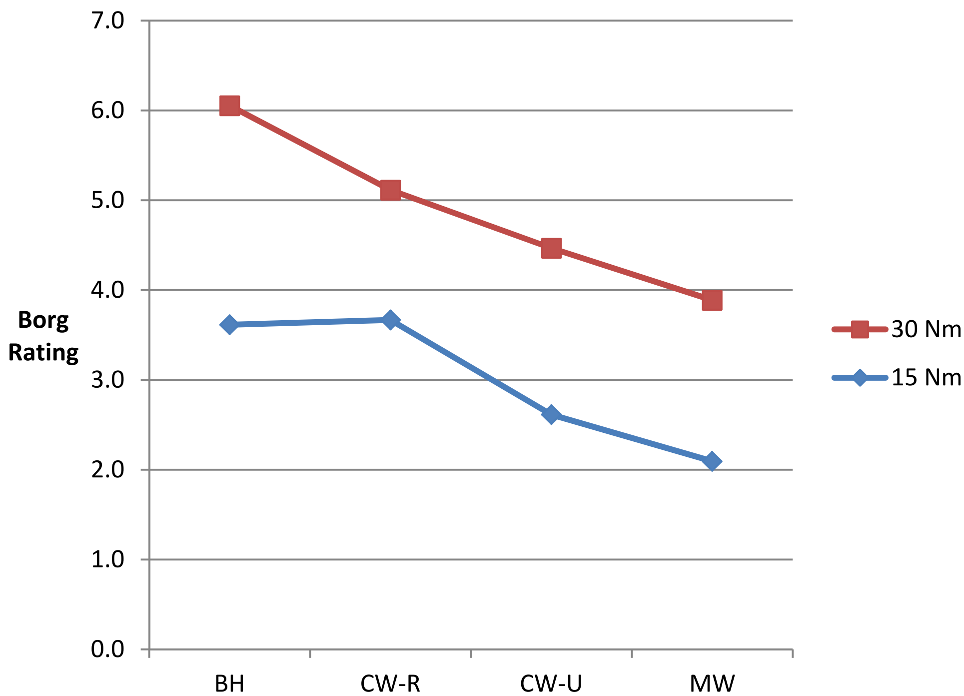


Figure 19: Average Borg-ratings associated with each valve-opening method at 15 Nm and 30 Nm.

Table 15: ANOVA results for the Borg-ratings. A highlighted p-value indicates that the corresponding effect is significant.

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
T	1	14	32.24	<.0001
M	3	84	14.40	<.0001
T*M	3	84	0.89	0.4501

The method main effect was examined by averaging the Borg-ratings of each method over both torque settings. Table 16 presents these averages and their associated standard deviations. The average Borg-ratings were, in ascending order, 3.0 for MW, 3.5 for CW-U, 4.4 for CW-R, and 4.8 for BH. Figure 20 provides a graphical representation of these averages for the different methods.

Table 16: The overall average Borg-rating and standard deviation associated with each valve-opening method.

Method	Borg-Rating	
	Average	S.D.
BH	4.8	2.1
CW-R	4.4	2.1
CW-U	3.5	1.5
MW	3.0	1.5

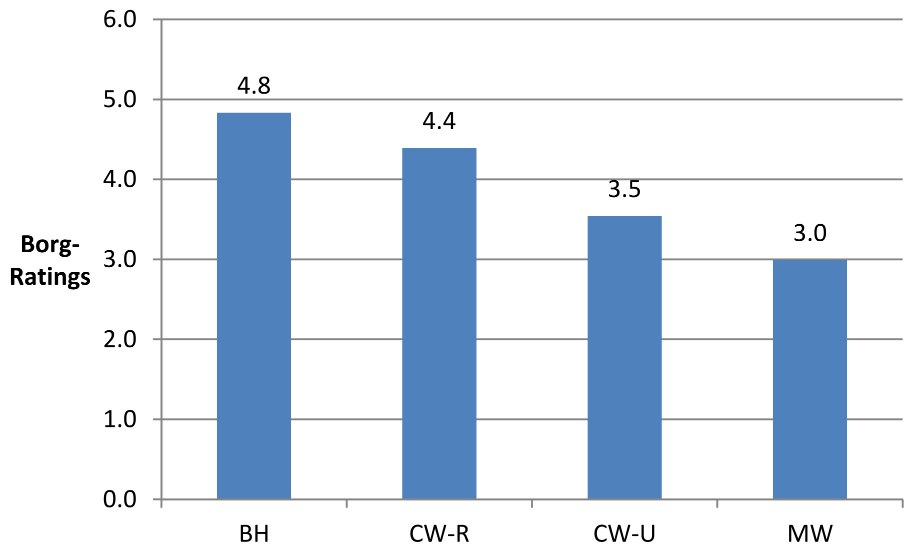


Figure 20: A bar graph of the average Borg-ratings associated with each valve-opening method averaged over 15 Nm and 30 Nm.

The method main effect was statistically significant for the Borg-ratings with a p-value less than 0.0001 (Table 15). This result indicates that at least one method is significantly different than the remaining methods, in terms of the average Borg-ratings. The Tukey test was performed to identify the specific methods that were statistically different from the other methods. According to the Tukey test (Table 17), BH and CW-R were not significantly different from each other. BH received an average Borg rating of 4.83, while CW-R received a Borg rating of 4.39. These values fall in between “somewhat difficult” and “difficult” on the Borg scale (Figure 7).

Both of these opening methods had significantly higher Borg ratings than CW-U and MW. The average Borg ratings for CW-U and MW were 3.54 and 2.99, respectively. In other words, CW-U was rated in between "moderate" and "somewhat difficult," while MW was rated as "moderate." MW received the lowest Borg-rating, meaning it was the least strenuous based on perception. However, according to the Tukey test, the difference between the MW and CW-U (0.55) was not large enough to be considered significant.

Table 17: Tukey-Kramer output for the Borg ratings of the method main effect.

M	**Estimate**	**Letter**	**Group**
BH	4.83	A	
CW-R	4.39	A	
CW-U	3.54		B
MW	2.99		B

The overall average Borg-rating at the higher torque was greater than the overall average Borg-rating at the lower torque. At 30 Nm, the overall average Borg rating was 4.9, while at 15 Nm, the overall average Borg rating was 3.0 (Table 18). This difference was found to be statistically significant with a p-value of 0.0001 (Table 15).

Table 18: The overall average Borg ratings and standard deviations associated with 15 Nm and 30 Nm.

Torque	Borg-Rating	
	Average	S.D.
15 Nm	3.0	1.7
30 Nm	4.9	1.9

5.4 EMG Results

During each experimental trial, EMG activities from the right and left anterior deltoids, trapezii, latissimi dorsi, and erector spinae muscles were measured. The maximum EMG activities of each muscle from the experimental trials were normalized to the maximum EMG activity of the corresponding muscle's RC. The following sections present the results of the maximum EMG activity of each muscle as a percentage of the muscle's maximum RC activity (%RC).

5.4.1 Right Anterior Deltoid

Table 19 presents the average maximum EMG activities of the right anterior deltoid associated with each valve-opening method at both torque levels. At 15 Nm, CW-R required the least muscle activity (57.5 %RC), followed by BH (63.6 %RC), MW (73.6 %RC), and CW-U (82.5 %RC). At 30 Nm, BH required the least muscle activity (77.1 %RC), followed by CW-R (82.3 %RC), MW (88.8 %RC), and CW-U (90.3 %RC). For all the methods, the average maximum EMG activities of the right anterior deltoid were higher at 30 Nm than at 15 Nm. From 15 Nm to 30 Nm, the average EMG activities increased by 13.6 %RC for BH, 24.8 %RC for CW-R, 7.7 %RC for CW-U, and 15.2 %RC for MW.

Table 19: The average maximum EMG activity of the right anterior deltoid and standard deviation associated with each valve-opening method at 15 Nm and 30 Nm.

Torque	Method	R. Ant Del (%RC)	
		Average	S.D.
15 Nm	BH	63.6	34.2
	CW-R	57.5	15.0
	CW-U	82.5	22.4
	MW	73.6	22.5
30 Nm	BH	77.1	32.7
	CW-R	82.3	31.9
	CW-U	90.3	34.7
	MW	88.8	33.5

Figure 21 presents a graph of the average maximum EMG activities of the right anterior deltoid associated with the different method-torque combinations. Although the trend across methods between the two torque levels differed, the difference was not large enough to be detected by ANOVA as a significant difference. The p-value of the interaction effect of method and torque was 0.4345 (Table 20). This finding suggests that torque and method are independent of each other and can be interpreted separately, in regards to the EMG activity of the right anterior deltoid.

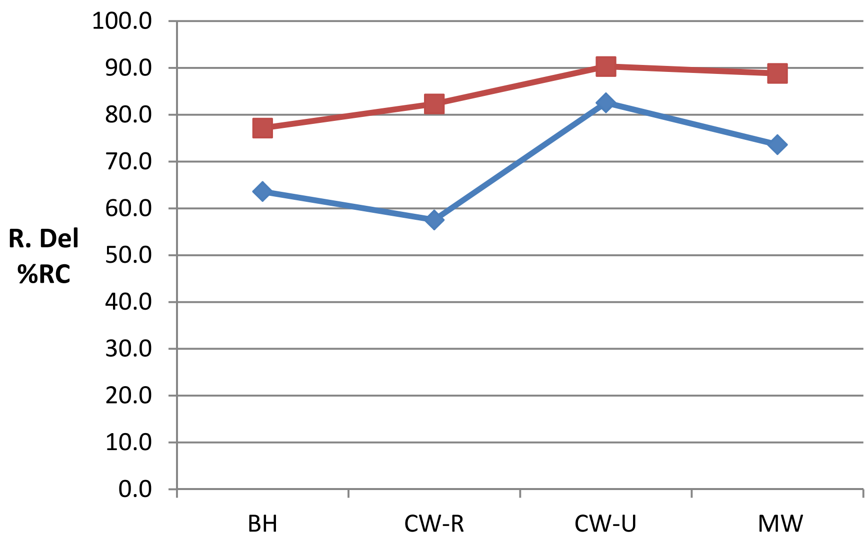


Figure 21: The average maximum EMG activities of the right anterior deltoid associated with each valve-opening method at 15 Nm and 30 Nm.

Table 20: ANOVA results for the right anterior deltoid. A highlighted p-value indicates that the corresponding effect is significant.

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
T	1	14	10.51	0.0059
M	3	84	5.03	0.0029
T*M	3	84	0.94	0.4245

To examine the method main effect, the average maximum EMG activities of the right anterior deltoid associated with each method were averaged over 15 Nm and 30 Nm. Table 21 presents these averages and their associated standard deviations. CW-R was associated with the least muscle activity (69.9 %RC), followed by BH (70.4 %RC), MW (81.2 %RC), and CW-U (86.4 %RC). Figure 22 illustrates these averages in a bar graph.

Table 21: The overall average maximum EMG activity of the right anterior deltoid and standard deviation associated with each valve-opening method.

Method	R. Ant Del (%RC)	
	Average	S.D.
BH	70.4	33.4
CW-R	69.9	24.9
CW-U	86.4	29.2
MW	81.2	28.5

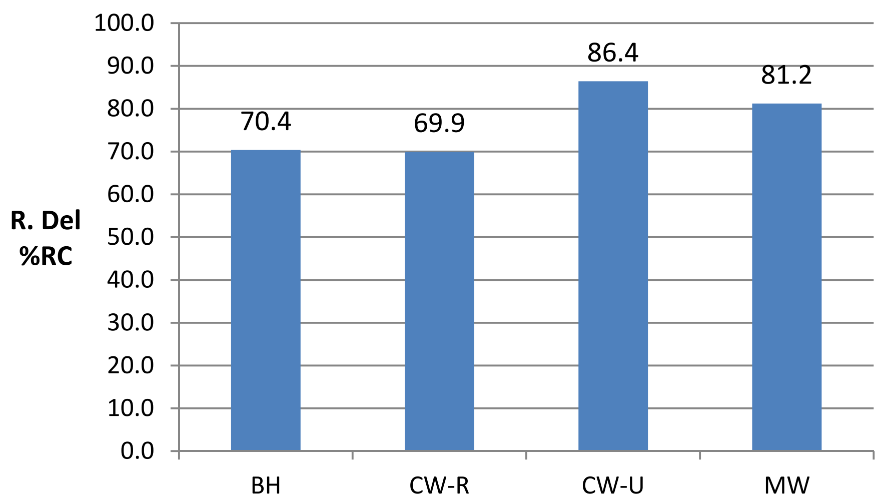


Figure 22: The average maximum EMG activity of the right anterior deltoid associated with each method averaged over both torques.

Unlike the interaction effect, the method main effect was statistically significant with a p-value less than 0.0029 (Table 20). This result indicates that at least one method is significantly different than the remaining methods in the average maximum EMG activity of the right anterior deltoid. To determine the sources of the significant differences between methods, the Tukey test was performed. Table 22 presents the Tukey results, grouping methods into different letter groups. Methods in different letter groups indicate that significant differences exist between the methods in terms of the right anterior deltoid EMG activity. According to the table, the only significant differences were found between CW-U & BH and CW-U & CW-R. The CW-U method required significantly greater muscle activity than BH and CW-R by 16 %RC and 16.5 %RC, respectively. The BH and CW-R methods produced almost equal levels of muscle activity, differing by only 0.5 %RC. No significant differences were detected between MW and the other methods.

Table 22: Tukey-Kramer output of the method main effect for the EMG activity of the right anterior deltoid.

M	Estimate	Letter Group	
CW-U	86.4	A	
MW	81.2	A	B
BH	70.4		B
CW-R	69.9		B

The torque main effect on the right anterior deltoid was also significant with a p-value of 0.0059 (Table 20). Table 23 shows the average maximum EMG activity of the right anterior deltoid associated with each torque averaged over all methods, and the table also provides the standard deviations associated with each average. The 30 Nm torque was associated with significantly higher EMG activity (84.6 %RC) than the 15 Nm torque (69.3%). From 15 Nm to 30 Nm, the EMG activity increased by an average of 15.3 %RC, which is equivalent to approximately a 22.0% increase.

Table 23: The overall average maximum EMG activities of the right anterior deltoid and standard deviations associated with 15 Nm and 30 Nm.

Torque	R. Ant Del (%RC)	
	Average	S.D.
15 Nm	69.3	24.5
30 Nm	84.6	33.2

5.4.2 Left Anterior Deltoid

Table 24 presents the average maximum EMG activities of the left anterior deltoid for each valve-opening method at both torque levels. At 15 Nm, BH was associated with the least muscle activity (18.9 %RC), followed by MW (56.8 %RC), CW-R (57.7 %RC), and finally CW-U (60.4 %RC). The trend at 30 Nm differed slightly from the trend at 15 Nm. At 30 Nm, BH was associated with least muscle activity (24.2 %RC), followed by CW-R (68.4 %RC), CW-U (69.2 %RC), and finally MW (69.6 %RC). For all the methods, the average maximum EMG activities of the left anterior deltoid were higher at 30 Nm than at 15 Nm. From 15 Nm to 30 Nm, the average EMG activities increased by 5.2 %RC for BH, 10.8 %RC for CW-R, 8.7 %RC for CW-U, and 12.8 %RC for MW.

Table 24: The average maximum EMG activity of the left anterior deltoid and standard deviation associated with each valve-opening method at 15 Nm and 30 Nm.

Torque	Method	L. Ant Del (%RC)	
		Average	S.D.
15 Nm	BH	18.9	8.8
	CW-R	57.7	27.8
	CW-U	60.4	32.3
	MW	56.8	28.7
30 Nm	BH	24.2	17.4
	CW-R	68.4	27.7
	CW-U	69.1	32.0
	MW	69.6	31.2

Figure 23 presents a graph of the average maximum EMG activities of the left anterior deltoid associated with the different method-torque combinations. Although the trend across methods between the two torque levels differed, the difference was not large enough to be detected by ANOVA as a significant difference. The p-value of the interaction effect of method and torque was 0.9043 (Table 25). This finding suggests that torque and method are independent of each other and can be interpreted separately, in regards to the EMG activity of the left anterior deltoid.

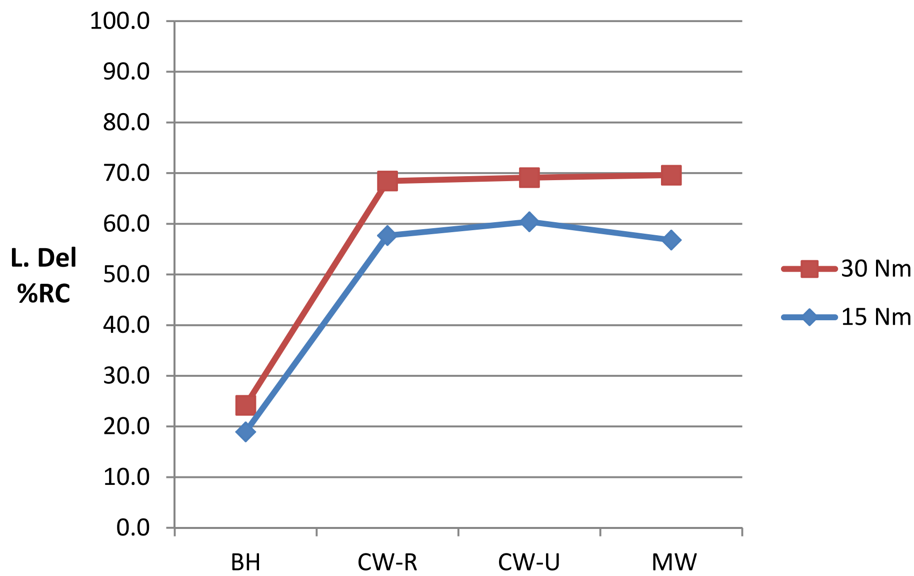


Figure 23: The average maximum EMG activities of the left anterior deltoid associated with each valve-opening method at 15 Nm and 30 Nm.

Table 25: ANOVA results for the left anterior deltoid. A highlighted p-value indicates that the corresponding effect is significant.

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
T	1	98	6.36	0.0132
M	3	98	32.13	<.0001
T*M	3	98	0.19	0.9043

To examine the method main effect, the average maximum EMG activities of the left anterior deltoid associated with each method were averaged over 15 Nm and 30 Nm. Table 26 presents these averages and their associated standard deviations, and Figure 24 illustrates these averages in a bar graph. BH was associated the least muscle activity of the left anterior deltoid (21.5 %RC), followed by CW-R (63.1 %RC), MW (63.2 %RC), and finally CW-U (64.8 %RC).

Table 26: The overall average maximum EMG activity of the left anterior deltoid and standard deviation associated with each valve-opening method.

Method	L. Ant Del (%RC)	
	Average	S.D.
BH	21.5	13.8
CW-R	63.1	27.8
CW-U	64.8	32.1
MW	63.2	30.0

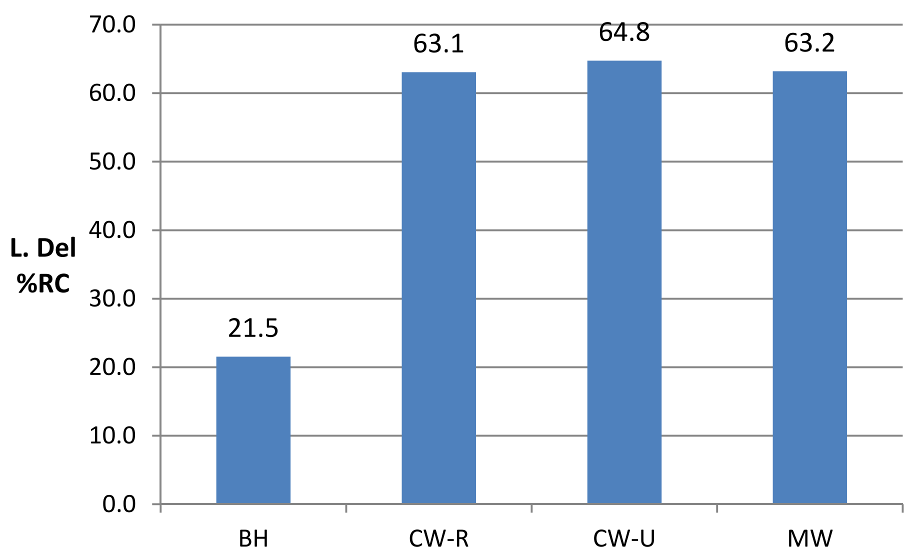


Figure 24: The average maximum EMG activity of the left anterior deltoid associated with each method averaged over both torques.

The method main effect was found to be significant for the left anterior deltoid with a p-value less than 0.0001. This result indicates that at least one method is significantly different than the remaining methods in the average maximum EMG activity of the left anterior deltoid. To determine the sources of the significant differences between methods, the Tukey test was performed. Table 27 summarizes the Tukey output for the left anterior deltoid, grouping together methods that lack significant differences between each other. No significant difference was detected among CW-R, CW-U, and MW. On the other hand, BH resulted with significantly less EMG activity than all the other methods.

Table 27: Tukey-Kramer output of the method main effect for the EMG activity of the left anterior deltoid.

M	Estimate	Letter Group	
CWU	64.8	A	
MW	63.2	A	
CWR	63.1	A	
BH	21.5		B

The torque main effect on the left anterior deltoid was also significant with a p-value of 0.0132 (Table 25). Table 28 shows the average maximum EMG activities of the left anterior deltoid associated with each torque averaged over all methods, and the table also provides the standard deviations associated with each average. The 30 Nm torque was associated with significantly higher EMG activity (57.8 %RC) than the 15 Nm torque (48.4%). From 15 Nm to 30 Nm, the EMG activity increased by 9.4 %RC, which is equivalent to approximately a 19.0% increase.

Table 28: The overall average maximum EMG activities of the left anterior deltoid and standard deviations associated with 15 Nm and 30 Nm.

Torque	L. Ant Del (%RC)	
	Average	S.D.
15 Nm	48.4	26.1
30 Nm	57.8	27.7

5.4.3 Right Trapezius

Table 29 shows the average maximum EMG activities of the right trapezius associated with each method-torque combination. At 15 Nm, CW-R required the least muscle activity (23.9 %RC), followed by BH (36.0 %RC), MW (50.1 %RC), and finally CW-U (60.1 %RC). At 30 Nm, almost a similar trend was found. CW-R required the least muscle activity (31.7 %RC), followed by BH (39.2 %RC), CW-U (53.5 %RC), and finally MW (54.6 %RC). For all the methods, except CW-U, the average maximum EMG activities of the right trapezius were higher at 30 Nm than at 15 Nm. From 15 Nm to 30 Nm, the average EMG activities increased by 3.2 %RC for BH, 7.9 %RC for CW-R, and 4.5 %RC for MW; whereas, the average EMG activity decreased for CW-U by 6.6 %RC.

Table 29: The average maximum EMG activity of the right trapezius and standard deviation associated with each valve-opening method at 15 Nm and 30 Nm.

Torque	Method	R. Trap (%RC)	
		Average	S.D.
15 Nm	BH	36.0	20.3
	CW-R	23.9	12.2
	CW-U	60.1	33.1
	MW	50.1	24.2
30 Nm	BH	39.2	19.8
	CW-R	31.7	18.1
	CW-U	53.5	28.1
	MW	54.6	38.9

Figure 25 presents a graph of the average maximum EMG activities of the right trapezius for the different method-torque combinations. Although the torques have different trends, the lines were almost parallel, suggesting the interaction effect between torque and method to be non-significant. According to the ANOVA results (Table 30), the interaction effect was in fact not significant with a p-value of 0.3953. This finding suggests that torque and method are independent of each other and can be interpreted separately, in regards to the EMG activity of the right trapezius.

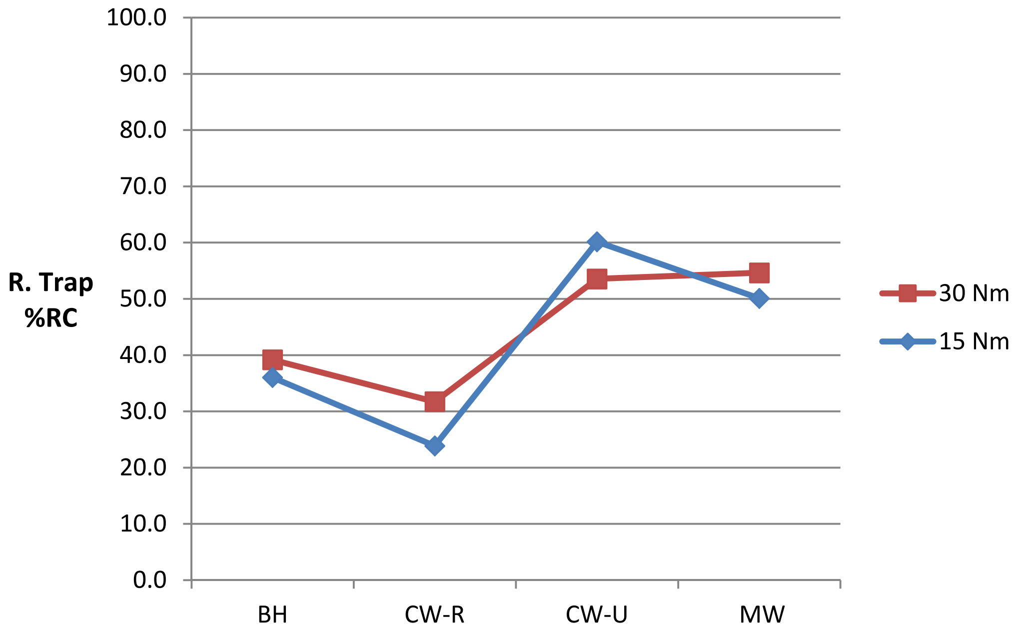


Figure 25: The average maximum EMG activities of the right trapezius associated with each valve-opening method at 15 Nm and 30 Nm.

Table 30: ANOVA results for the right trapezius. A highlighted p-value indicates that the corresponding effect is significant.

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
T	1	14	0.39	0.5413
M	3	84	18.71	<.0001
T*M	3	84	1.00	0.3953

The average maximum EMG activities of the right trapezius associated with each method were averaged over 15 Nm and 30 Nm to examine the method main effect. Table 31 presents these averages and their associated standard deviations, and Figure 26 illustrates these averages in a bar graph. CW-R was associated with least muscle activation (27.8 %RC), followed by BH (37.6 %RC), MW (52.4 %RC), and finally CW-U (56.8 %RC).

Table 31: The overall average maximum EMG activity of the right trapezius and standard deviation associated with each valve-opening method.

Method	R. Trap (%RC)	
	Average	S.D.
BH	37.6	20.1
CW-R	27.8	15.5
CW-U	56.8	30.7
MW	52.4	32.4

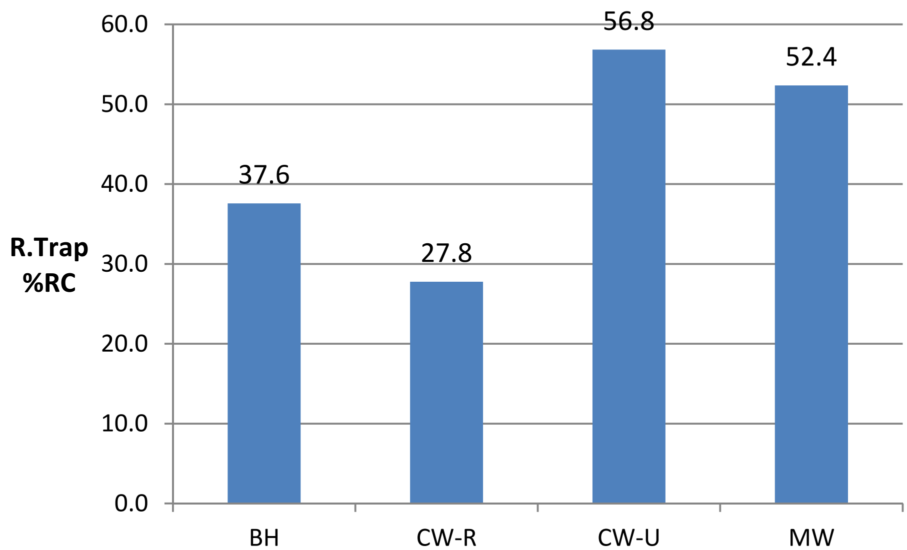


Figure 26: The average maximum EMG activity of the right trapezius associated with each method averaged over both torques.

The method main effect for the EMG activity of the right trapezius was significant ($p < 0.0001$), indicating that at least one method was significantly different than the other methods. According to the Tukey results (Table 32), CW-R and BH were not significantly different from each other, and also MW and CW-U were not significantly different from each other. However, both CW-R and BH were associated with significantly less EMG activity than MW and CW-U.

Table 32: Tukey-Kramer output of the method main effect for the EMG activity of the right trapezius.

M	Estimate	Letter Group	
CWU	56.8	A	
MW	52.4	A	
BH	37.6		B
CWR	27.8		B

Unlike the right and left anterior deltoids, the torque effect on the right trapezius was not significant with a p-value of 0.5413 (Table 30). Table 33 shows the average maximum EMG activities of the right trapezius associated with each torque averaged over all methods, and the table also provides the standard deviations associated with each average. The maximum EMG activity averaged over all methods was 42.5 %RC at 15 Nm and 44.8 %RC at 30 Nm. Although the EMG activity was different between the two methods, the difference (2.3 %RC) was not large enough in the ANOVA test to be detected as significant.

Table 33: The overall average maximum EMG activities of the right trapezius and standard deviations associated with 15 Nm and 30 Nm.

Torque	R. Trap (%RC)	
	Average	S.D.
15 Nm	42.5	23.7
30 Nm	44.8	27.5

5.4.4 Left Trapezius

Table 34 presents the average maximum EMG activities of the left trapezius muscle and the standard deviations associated with each method-torque combination. At 15 Nm, BH required the least muscle activity (22.8 %RC), followed by CW-R (25.5 %RC), CW-U (53.8 %RC), and

MW (63.0 %RC). A similar trend was found at 30 Nm, where BH required the least muscle activity (29.0 %RC), followed by CW-R (30.9 %RC), CW-U (56.4 %RC), and MW (77.3 %RC). For all the methods, the average maximum EMG activities of the left trapezius were higher at 30 Nm than at 15 Nm. From 15 Nm to 30 Nm, the average EMG activities increased by 6.2 %RC for BH, 5.4 %RC for CW-R, 2.6 %RC for CW-U, and 14.3 %RC for MW.

Table 34: The average maximum EMG activity of the left trapezius and standard deviation associated with each valve-opening method at 15 Nm and 30 Nm.

Torque	Method	L. Trap (%RC)	
		Average	S.D.
15 Nm	BH	22.8	22.7
	CW-R	25.5	20.0
	CW-U	53.8	31.6
	MW	63.0	36.7
30 Nm	BH	29.0	25.2
	CW-R	30.9	24.0
	CW-U	56.4	37.5
	MW	77.3	33.9

Figure 27 presents a graph of the average maximum EMG activity of the left trapezius muscle associated with each method at 15 Nm and 30 Nm. The lines for both torques were almost parallel, suggesting the interaction effect between torque and method to be non-significant. According to the ANOVA test (Table 35), the p-value of the interaction effect was 0.6424, which is not significant. This result means that the torque and method effects are independent of each other and can be interpreted separately, in regards to the EMG activity of the left trapezius.

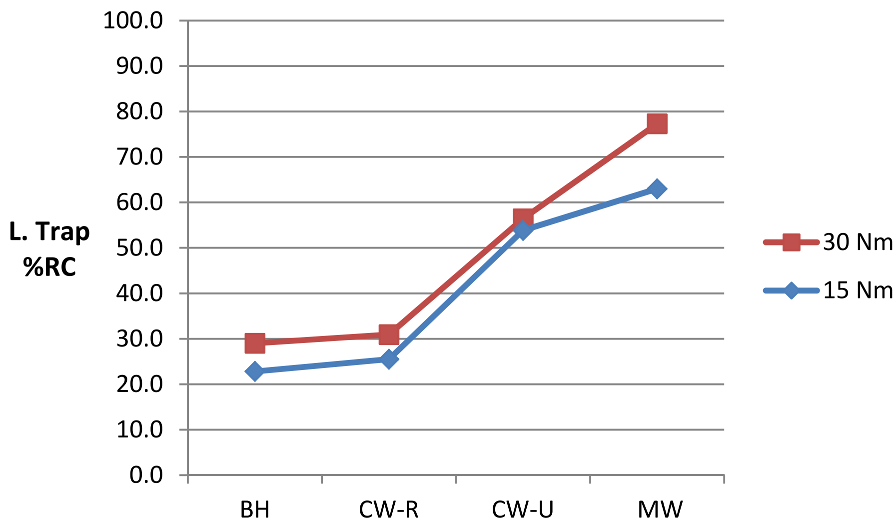


Figure 27: The average maximum EMG activities of the left trapezius associated with each valve-opening method at 15 Nm and 30 Nm.

Table 35: ANOVA results for the left trapezius. A highlighted p-value indicates that the corresponding effect is significant.

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
T	1	98	4.50	0.0365
M	3	98	40.79	<.0001
T*M	3	98	0.56	0.6424

To examine the method main effect, the average maximum EMG activities of the left trapezius associated with each method were averaged over 15 Nm and 30 Nm. Table 36 presents these averages and their associated standard deviations. The BH method required the least muscle activation of the left trapezius (25.9 %RC), followed by CW-R (28.2 %RC), CW-U (55.1 %RC), and MW (70.2 %RC). Figure 28 shows the overall averages of each method in a bar graph.

Table 36: The overall average maximum EMG activity of the left trapezius and standard deviation associated with each valve-opening method.

Method	L. Trap (%RC)	
	Average	S.D.
BH	25.9	24.0
CW-R	28.2	22.1
CW-U	55.1	34.7
MW	70.2	35.4

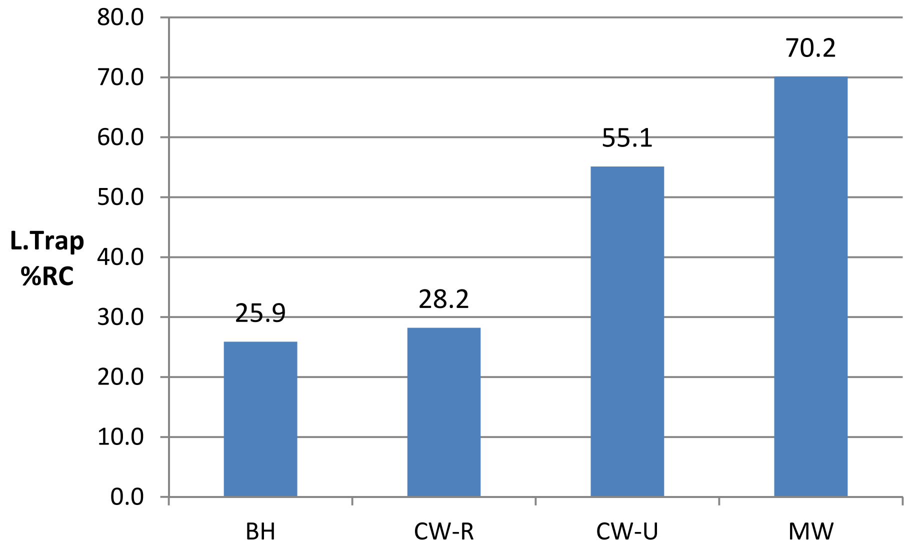


Figure 28: The average maximum EMG activity of the left trapezius associated with each method averaged over both torques.

Unlike the interaction effect, the method main effect was significant with a p-value less than 0.0001 (Table 35), suggesting that at least one method differed from the remaining methods. To determine the sources of the significant differences between methods, the Tukey test was performed (Table 37). No significant difference was detected in the Tukey tests between BH and CW-R; the difference between the two methods was only 2.3 %RC. However, all other pair wise comparisons between methods were detected as significant.

Table 37: Tukey output of the method main effect for the EMG activity of the left trapezius.

M	Estimate	Letter Group		
MW	70.2	A		
CWU	55.1		B	
CWR	28.2			C
BH	25.9			C

In the ANOVA test, the torque main effect was also significant with a p-value of 0.0365 (Table 35). Table 38 shows the average maximum EMG activities of the left trapezius associated with each torque averaged over all methods, and the table also provides the standard deviations associated with each average. The overall average EMG activity of the left trapezius at 15 Nm was 41.3 %RC. This EMG level was significantly less than the overall average EMG activity associated with 30 Nm, which was 48.4 %RC. This is a difference of 7.1 %RC between the two torques, or in other words, from 15 Nm to 30 Nm, the average EMG level increased by 17.2%.

Table 38: The overall average maximum EMG activities of the left trapezius and standard deviations associated with 15 Nm and 30 Nm.

Torque	L. Trap (%RC)	
	Average	S.D.
15 Nm	41.3	28.6
30 Nm	48.4	30.7

5.4.5 Right Latissimus Dorsi

Table 39 presents the average maximum EMG activities of the right latissimus dorsi and the standard deviations associated with each method-torque combination. At 15 Nm, CW-R required the lowest EMG activity of the right latissimus dorsi (27.0 %RC), followed by CW-U (39.6

%RC), BH (39.7 %RC), and finally MW (47.6 %RC). At 30 Nm, BH was associated with the lowest EMG activity (38.0 %RC), followed by CW-R (40.3 %RC), MW (42.2 %RC), and finally CW-U (49.7 %RC). From 15 to 30 Nm, the average maximum EMG activity of the right latissimus dorsi increased when using CW-R and CW-U by 13.3% RC and 10.1 %RC, respectively; whereas, for the BH and MW methods, the average maximum EMG activity decreased by 1.6 %RC and 5.4 %RC, respectively.

Table 39: The average maximum EMG activity of the right latissimus dorsi and standard deviation associated with each valve-opening method at 15 Nm and 30 Nm.

Torque	Method	R. Lat (%RC)	
		Average	S.D.
15 Nm	BH	39.7	27.3
	CW-R	27.0	20.3
	CW-U	39.6	37.4
	MW	47.6	54.5
30 Nm	BH	38.0	27.9
	CW-R	40.3	29.4
	CW-U	49.7	38.9
	MW	42.2	22.7

Figure 29 presents a graph of the average maximum EMG activities of the right latissimus dorsi muscle associated with each method at 15 Nm and 30 Nm. The EMG trends between 15 Nm and 30 Nm appear to differ across the four methods. However, according to the ANOVA test (Table 40), the p-value of the interaction effect was 0.2758, which is not significant. This result means that the torque and method effects are independent of each other and can be interpreted separately, in regards to the EMG activity of the right latissimus dorsi.

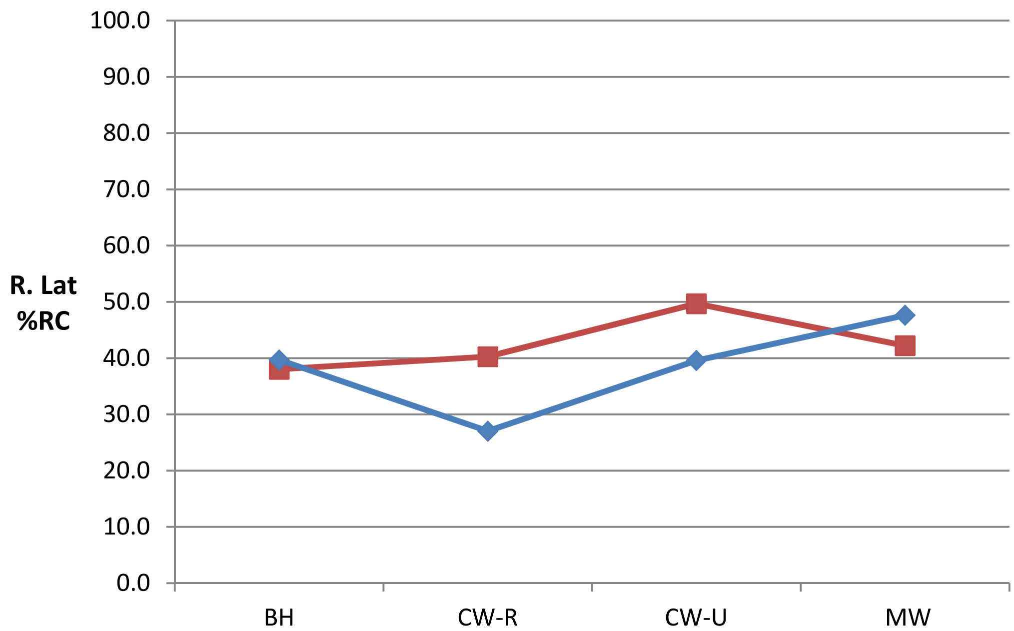


Figure 29: The average maximum EMG activities of the right latissimus dorsi associated with each valve-opening method at 15 Nm and 30 Nm.

Table 40: ANOVA results for the right latissimus dorsi. None of the effects are significant.

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
T	1	14	0.42	0.5269
M	3	84	1.86	0.1419
T*M	3	84	1.31	0.2758

Table 41 presents the overall average maximum EMG activities of the right latissimus dorsi associated with each method, and the table also provides the standard deviations associated with each average. Figure 30 shows these averages in a bar graph representation. The CW-R method required the least muscle activation of the right latissimus dorsi (33.6 %RC), followed by BH (38.8 %RC), CW-U (44.6 %RC), and MW (44.9 %RC). According to the ANOVA results (Table 40), the method main effect was not significant with a p-value of 0.1419. This result indicates that the average EMG activities of the right latissimus dorsi associated with each method are not significantly different from each other.

Table 41: The overall average maximum EMG activity of the right latissimus dorsi and standard deviation associated with each valve-opening method.

Method	R. Lat (%RC)	
	Average	S.D.
BH	38.8	27.6
CW-R	33.6	25.3
CW-U	44.6	38.1
MW	44.9	41.7

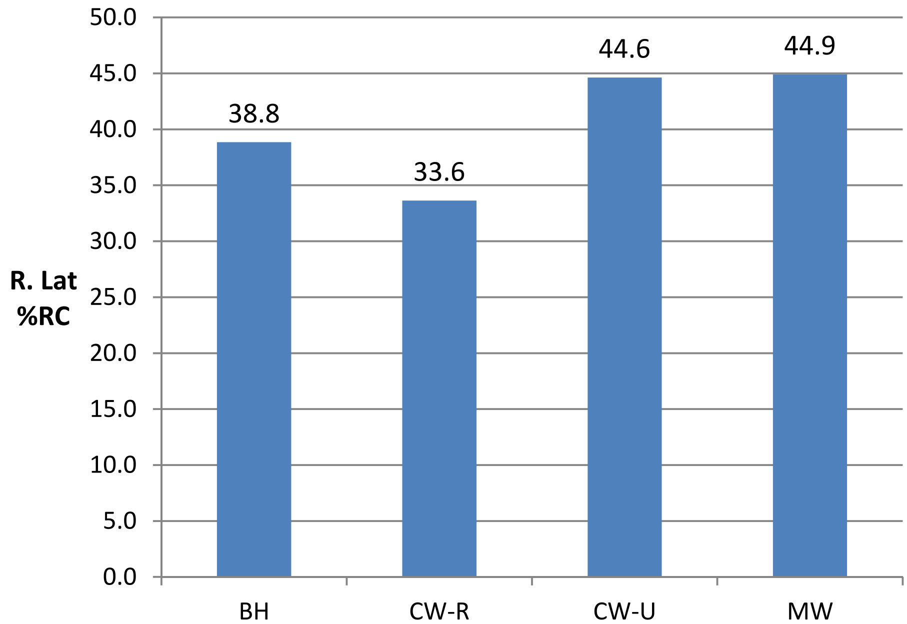


Figure 30: The average maximum EMG activity of the right latissimus dorsi associated with each method averaged over both torques.

Also, the torque main effect was not significant with a p-value of 0.5269. This result suggests that the overall averages of the EMG activity of the right latissimus dorsi at 15 Nm and 30 Nm did not differ. Table 42 presents these averages and their associated standard deviations. The average maximum EMG activity of the right latissimus dorsi was 38.5 %RC at 15 Nm and 42.5 %RC at 30 Nm. This is a difference of 4.0 %RC between the two torques, or in other words, from 15 Nm to 30 Nm, the average EMG level increased by 10.4%.

Table 42: The overall average maximum EMG activities of the right latissimus dorsi and standard deviations associated with 15 Nm and 30 Nm.

Torque	R. Lat (%RC)	
	Average	S.D.
15 Nm	38.5	37.2
30 Nm	42.5	30.3

5.4.6 Left Latissimus Dorsi

Table 43 presents the average maximum EMG activities of the left latissimus dorsi muscle and the standard deviations associated with each method-torque combination. At 15 Nm, the CW-R resulted in the least muscle activity (37.3 %RC), followed by MW (42.8 %RC), CW-U (49.5 %RC), and BH (62.6 %RC). At 30 Nm, the least muscle activity was found using the CW-R (42.6 %RC), CW-U (62.1 %RC), MW (71.6 %RC), and finally BH (84.7 %RC). For all the methods, the average maximum EMG activities of the left latissimus dorsi were higher at 30 Nm than at 15 Nm. From 15 Nm to 30 Nm, the average EMG activities increased by 22.5 %RC for BH, 5.3 %RC for CW-R, 12.5 %RC for CW-U, and 28.8 %RC for MW.

Figure 31 presents the average maximum EMG activity of the left latissimus dorsi muscle associated with each method and torque. Although the trends between the two torques differed across the methods, the difference was not large enough to be detected as significant by the ANOVA test (Table 44). The interaction effect between torque and method was associated with a non-significant p-value of 0.1869. This result means that the torque and method effects are independent of each other and can be interpreted separately, in regards to the EMG activity of the left latissimus dorsi.

Table 43: The average maximum EMG activity of the left latissimus dorsi and standard deviation associated with each valve-opening method at 15 Nm and 30 Nm.

Torque	Method	L. Lat (%RC)	
		Average	S.D.
15 Nm	BH	62.2	31.8
	CW-R	37.3	26.3
	CW-U	49.5	30.8
	MW	42.8	23.3
30 Nm	BH	84.7	42.8
	CW-R	42.6	18.4
	CW-U	62.1	36.0
	MW	71.6	31.0

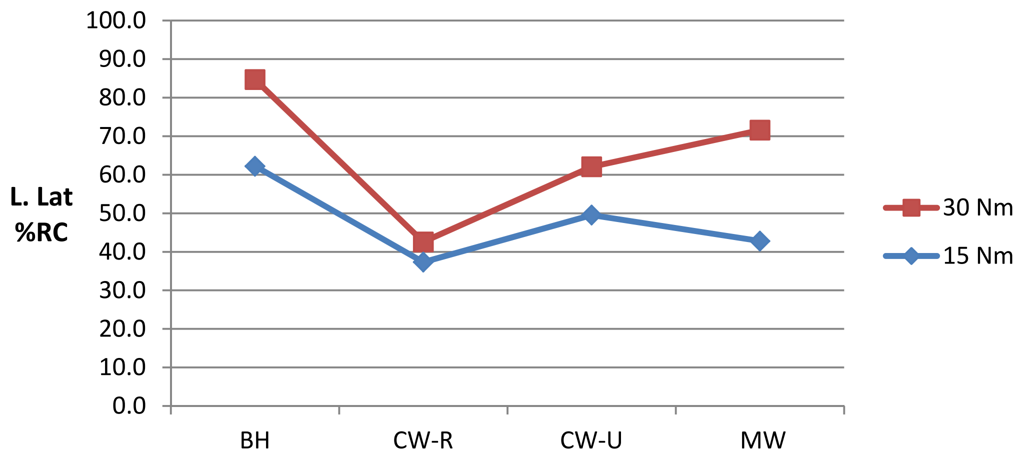


Figure 31: The average maximum EMG activities of the left latissimus dorsi associated with each valve-opening method at 15 Nm and 30 Nm.

Table 44: ANOVA results for the left latissimus dorsi. A highlighted p-value indicates that the corresponding effect is significant.

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
T	1	98	17.91	<.0001
M	3	98	11.26	<.0001
T*M	3	98	1.63	0.1869

To examine the method main effect, the average maximum EMG activities of the left latissimus dorsi associated with each method were averaged over 15 Nm and 30 Nm. Table 45 presents these averages and their associated standard deviations, and Figure 32 illustrates these averages in a bar graph. The CW-R method required the least muscle activation of the left latissimus dorsi (40.0 %RC), followed by CW-U (55.8 %RC), MW (57.2 %RC), and BH (73.5 %RC).

Table 45: The overall average maximum EMG activity of the left latissimus dorsi and standard deviation associated with each valve-opening method.

Method	L. Lat (%RC)	
	Average	S.D.
BH	73.5	37.7
CW-R	40.0	22.7
CW-U	55.8	33.5
MW	57.2	27.4

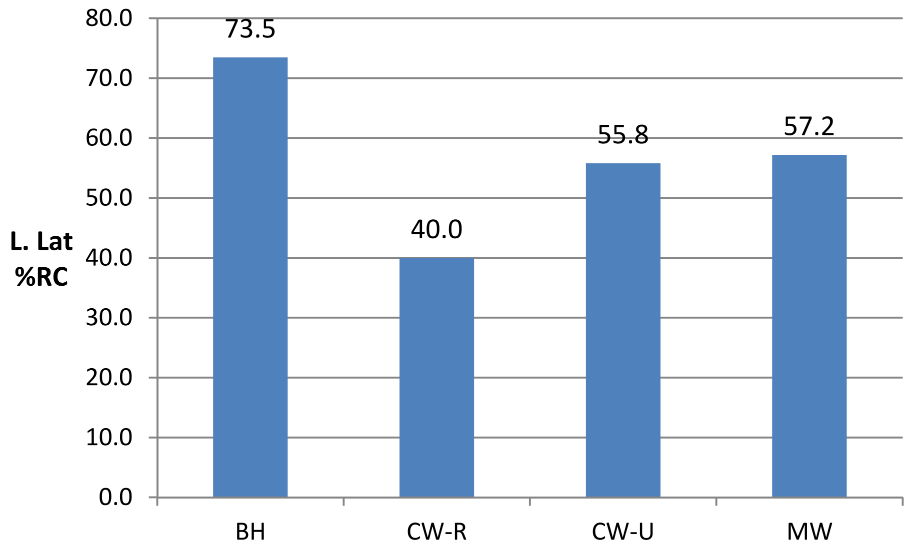


Figure 32: The average maximum EMG activity of the left latissimus dorsi associated with each method averaged over both torques.

The method main effect was significant with a p-value less than 0.0001, suggesting that at least one method differed significantly from the remaining methods in terms of the EMG activity of the left latissimus dorsi. According to the Tukey test (Table 46), the CW-R method had significantly lower EMG activity than all other methods (40.0 %RC). Following the CW-R method, the CW-U (55.8 %RC) and MW (57.2 %RC) were approximately equal in EMG activity, and no significant difference was detected between the two methods. Finally, the BH method was found to have significantly higher EMG activity (73.5 %RC) than all other methods.

Table 46: Tukey-Kramer output of the method main effect for the EMG activity of the left latissimus dorsi.

M	Estimate	Letter Group		
BH	73.5	A		
MW	57.2		B	
CWU	55.8		B	
CWR	40.0			C

Also, the torque main effect was found to be significant with a p-value less than 0.0001 (Table 44). Table 47 shows the average maximum EMG activities of the left latissimus dorsi associated with each torque averaged over all methods, and the table also provides the standard deviations associated with each average. The EMG activity averaged over all methods at 30 Nm (65.2 %RC) was found to be significantly larger than the EMG activity at 15 Nm (48.0 %RC). A 17.2 %RC difference was found between the two methods. In other words, when the torque level was doubled from 15 Nm to 30 Nm, the average EMG activity of the left latissimus dorsi muscle increased by approximately 35.8%.

Table 47: The overall average maximum EMG activities of the left latissimus dorsi and standard deviations associated with 15 Nm and 30 Nm.

Torque	L. Lat (%RC)	
	Average	S.D.
15 Nm	48.0	28.2
30 Nm	65.2	33.3

5.4.7 Right Erector Spinae

Table 48 presents the average maximum EMG activities of the right erector spinae muscle and the standard deviations associated with each method-torque combination. At 15 Nm, BH required the least muscle activity (40.8 %RC), followed by CW-R (48.1 %RC), MW (55.3 %RC), and CW-U (60.4 %RC). A similar trend was found at 30 Nm, where BH required the least muscle activity (44.0 %RC), followed by CW-R (44.1 %RC), MW (58.6 %RC), and CW-U (65.4 %RC). For all the methods, except the CW-R method, the average maximum EMG activities of the right erector spinae were higher at 30 Nm than at 15 Nm. From 15 Nm to 30 Nm, the average EMG activities increased by 3.2 %RC for BH, 5.0 %RC for CW-U, and 3.4 %RC for MW; whereas, the average EMG activity decreased for the CW-R method by 4.0 %RC.

Table 48: The average maximum EMG activity of the right erector spinae and standard deviation associated with each valve-opening method at 15 Nm and 30 Nm.

Torque	Method	R. ES (%RC)	
		Average	S.D.
15 Nm	BH	40.8	14.3
	CW-R	48.1	19.5
	CW-U	60.4	21.6
	MW	55.3	18.4
30 Nm	BH	44.0	20.9
	CW-R	44.1	11.3
	CW-U	65.4	25.7
	MW	58.6	25.7

Figure 33 presents a graph of the average maximum EMG activities of the right erector spinae muscle associated with each opening method at both torque levels. The graph shows the EMG trends for each torque across methods to be almost parallel. This finding is supported by the ANOVA test (Table 49), which found the torque and method interaction effect to have a non-significant p-value of 0.6328. This result indicates that the torque and method effects are independent of each other and can be interpreted separately, in regards to the EMG activity of the right erector spinae.

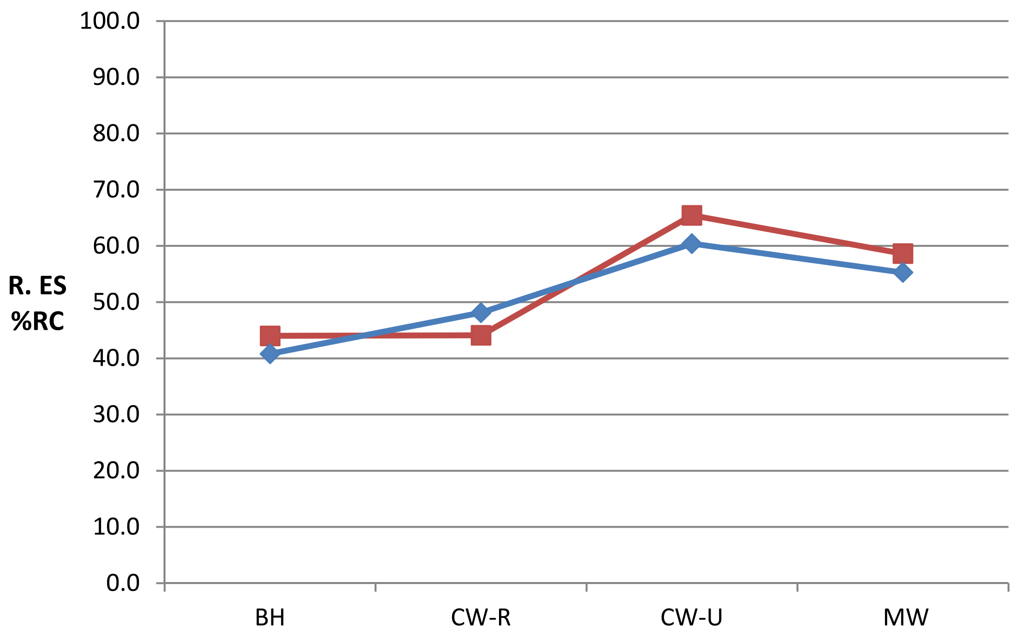


Figure 33: The average maximum EMG activities of the right erector spinae associated with each valve-opening method at 15 Nm and 30 Nm.

Table 49: ANOVA results for the right erector spinae. A highlighted p-value indicates that the corresponding effect is significant.

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
T	1	98	0.51	0.4784
M	3	98	12.79	<.0001
T*M	3	98	0.57	0.6328

The average maximum EMG activities of the right erector spinae associated with each method were averaged over 15 Nm and 30 Nm to examine the method main effect. Table 50 presents these averages and their associated standard deviations, and Figure 34 presents these averages in a bar graph. BH was associated with the least muscle activity (42.4 %RC), followed by CW-R (46.1 %RC), MW (56.9 %RC), and finally CW-U (62.9 %RC).

Table 50: The overall average maximum EMG activity of the right erector spinae and standard deviation associated with each valve-opening method.

Method	R. ES (%RC)	
	Average	S.D.
BH	42.4	17.9
CW-R	46.1	15.9
CW-U	62.9	23.7
MW	56.9	22.3

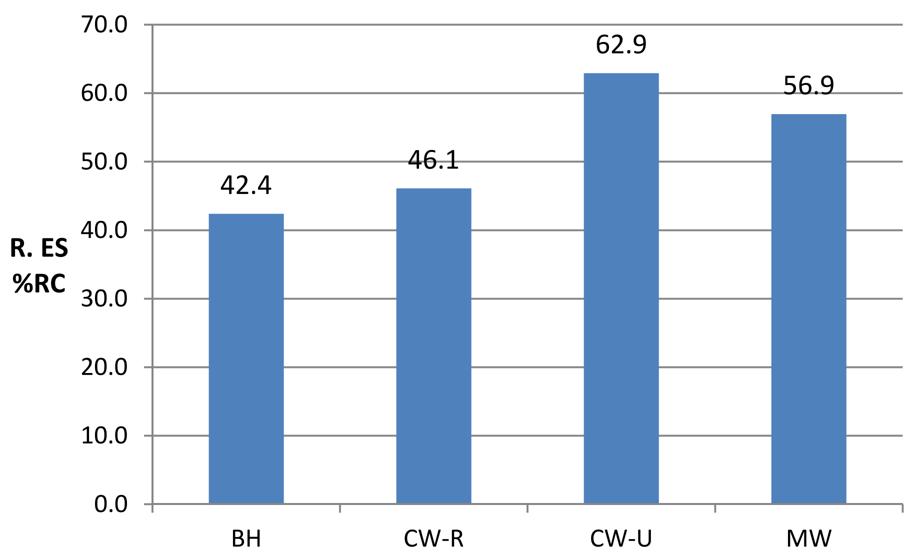


Figure 34: The average maximum EMG activity of the right erector spinae associated with each method averaged over both torques.

The method main effect was significant with a p-value less than 0.0001, indicating that at least one method differed than the remaining methods in terms of the EMG activity of the right erector spinae muscle. According to the Tukey test (Table 51), both BH and CW-R had significantly lower EMG activities than CW-U and MW. However, no significant differences were detected between BH and CW-R and between MW and CW-U.

Table 51: Tukey-Kramer output of the method main effect for the EMG activity of the right erector spinae.

M	Estimate	Letter Group	
CWU	62.9	A	
MW	56.9	A	
CWR	46.1		B
BH	42.4		B

The torque main effect was not significant with a p-value of 0.4784, indicating that no significant difference exists between the average EMG activity at 15 Nm and 30 Nm. This finding can also be learned from Figure 33, which shows the two torque lines almost overlapping across all methods. Table 52 shows the average maximum EMG activities of the right erector spinae associated with each torque averaged over all methods, and the table also provides the standard deviations associated with each average. The overall averages were 51.1 %RC at the lower torque and 53.0% at the higher torque. This difference (1.9 %RC) was not detected in the ANOVA test as statistically significant.

Table 52: The overall average maximum EMG activities of the right erector spinae and standard deviations associated with 15 Nm and 30 Nm.

Torque	R. ES (%RC)	
	Average	S.D.
15 Nm	51.1	18.6
30 Nm	53.0	21.7

5.4.8 Left Erector Spinae

Table 53 presents the average maximum EMG activities of the left erector spinae muscle and the standard deviations associated with each method-torque combination. At 15 Nm, BH required the least muscle activity (51.0 %RC), followed by CW-R (51.4 %RC), MW (52.9 %RC), and CW-U (57.9 %RC). At 30 Nm, CW-R required the least muscle activity (49.2 %RC), followed by BH (53.4 %RC), MW (64.0 %RC), and CW-U (68.4 %RC). For all the methods, except the CW-R method, the average maximum EMG activities of the left erector spinae were higher at 30 Nm than at 15 Nm. From 15 Nm to 30 Nm, the average EMG activities increased by 2.4 %RC for BH, 10.5 %RC for CW-U, and 11.1 %RC for MW; whereas, the average EMG activity decreased for the CW-R method by 2.2 %RC.

Table 53: The average maximum EMG activity of the left erector spinae and standard deviation associated with each valve-opening method at 15 Nm and 30 Nm.

Torque	Method	L. ES (%RC)	
		Average	S.D.
15 Nm	BH	51.0	37.9
	CW-R	51.4	32.9
	CW-U	57.9	23.2
	MW	52.9	19.0
30 Nm	BH	53.4	23.9
	CW-R	49.2	16.8
	CW-U	68.4	21.9
	MW	64.0	20.1

Figure 35 presents a graph of the average maximum EMG activity of the left erector spinae muscle associated with each method at both torques. Although the trends across methods between the two torques seem to differ, the ANOVA test did not detect a significant interaction effect between torque and method with a p-value of 0.4456 (Table 54). This result suggests that the torque and method effects are independent of each other and can be interpreted separately, in regards to the EMG activity of the left erector spinae.

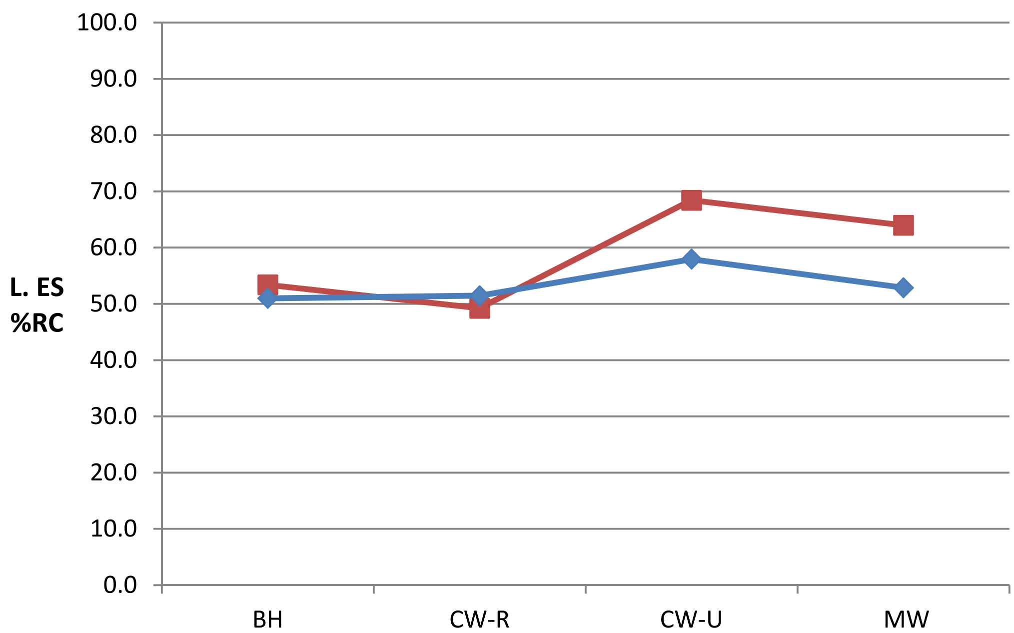


Figure 35: The average maximum EMG activities of the left erector spinae associated with each valve-opening method at 15 Nm and 30 Nm.

Table 54: ANOVA results for the left erector spinae. A highlighted p-value indicates that the corresponding effect is significant.

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
T	1	98	2.55	0.1136
M	3	98	2.98	0.0352
T*M	3	98	0.90	0.4456

To examine the method main effect, the average maximum EMG activities of the left erector spinae associated with each method were averaged over 15 Nm and 30 Nm. Table 55 presents these averages and their associated standard deviations, and Figure 36 shows these averages in a bar graph representation. The CW-R method required the least muscle activation of the left erector spinae (50.3 %RC), followed by BH (52.2 %RC), MW (58.4 %RC), and CW-U (63.2 %RC).

Table 55: The overall average maximum EMG activity of the left erector spinae and standard deviation associated with each valve-opening method.

Method	L. ES (%RC)	
	Average	S.D.
BH	52.2	31.7
CW-R	50.3	26.1
CW-U	63.2	22.6
MW	58.4	19.6

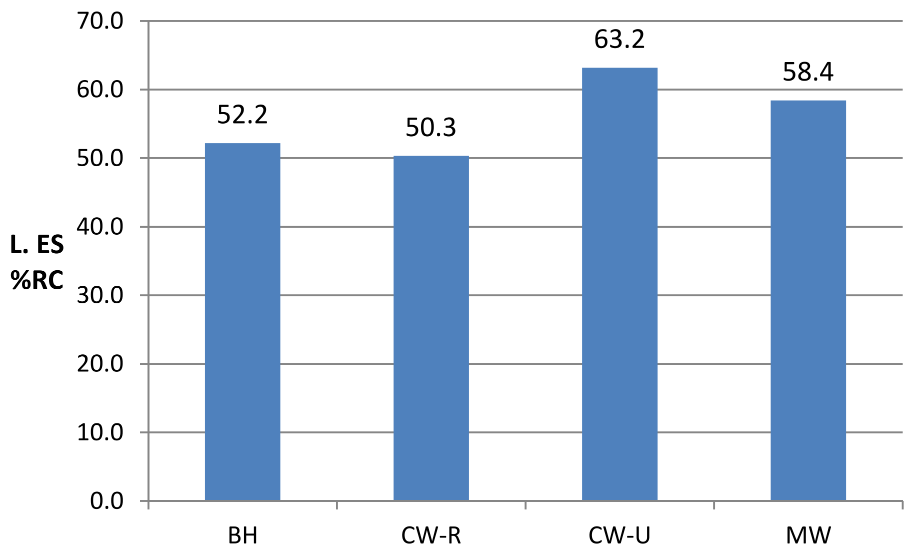


Figure 36: The average maximum EMG activity of the left erector spinae associated with each method averaged over both torques.

The method main effect was significant (p = 0.0352) for the left erector spinae muscle (Table 54), suggesting that at least one method differed from the remaining methods. To determine the sources of the significant differences between methods, the Tukey test was performed and the results are summarized in Table 56. The only pair-wise comparison found to be significant was between the CW-U and CW-R method. On average, CW-R was associated with 12.9% RC more EMG activity than CW-U.

Table 56: Tukey-Kramer output of the method main effect for the EMG activity of the left erector spinae.

M	Estimate	Letter Group	
CWU	63.2	A	
MW	58.4	A	B
BH	52.2	A	B
CWR	50.3		B

The torque main effect was not significant with a p-value of 0.1136, suggesting that no significant difference exists in the average maximum EMG activities of the left erector spinae at 15 Nm and 30 Nm. Table 57 shows the average maximum EMG activities of the left erector spinae associated with each torque averaged over all methods, and the table also provides the standard deviations associated with each average. The overall averages were 53.3 %RC at the lower torque and 58.8% at the higher torque, which is a difference of 5.5 %RC. Although a difference existed, it was not large enough to be detected by ANOVA as a significant difference.

Table 57: The overall average maximum EMG activities of the left erector spinae and standard deviations associated with 15 Nm and 30 Nm.

Torque	L. ES (%RC)	
	Average	S.D.
15 Nm	53.3	29.2
30 Nm	58.8	20.9

5.5 Testing of Hypotheses

This research proposed three different hypotheses for each dependent variable. Hypothesis 1 tested the method (M) main effect whether it had any significant difference(s) among the means of the BH, CW-R, CW-U, and MW methods. Hypothesis 2 tested the torque (T) main effect to determine whether a significant difference existed between the means of 15 Nm and 30 Nm. Hypothesis 3 tested the interaction effect between torque and method (T*M) to determine whether a significant interaction effect existed between torque and method.

Table 58 summarizes the p-values associated with each effect for each dependent variable investigated. Highlighted values in the table represent significant p-values. The interaction effect was not significant for any of the dependent variables, indicating that the effects of torque and method were independent of each other. In other words, the null hypothesis of the interaction effect (Hypothesis 3: There is no significant interaction between the method and torque effects) was not rejected for any of the dependent variables. Since the interaction effect was not significant, the method and torque main effects were each examined for statistical significance.

Table 58: The p-values associated with each dependent variable and hypothesis. Highlighted values represent significant p-values.

Hypotheses (Effects)	Time	Borg	R. Ant Del	L. Ant Del	R. Trap	L. Trap	R. Lat	L. Lat	R. ES	L. ES
Hypothesis 1 (M)	<.0001	<.0001	0.0029	<.0001	<.0001	<.0001	0.1419	<.0001	<.0001	0.0352
Hypothesis 2 (T)	0.0042	<.0001	0.0059	0.0132	0.5413	0.0365	0.5269	<.0001	0.4784	0.1136
Hypothesis 3 (T*M)	0.6954	0.4501	0.4245	0.9043	0.3953	0.6424	0.2758	0.1869	0.6328	0.4456

The method main effect was significant for all the dependent variables, except the EMG activity of the right latissimus dorsi. In other words, the null hypothesis for the method main effect (Hypothesis 1: The means of all the valve-opening methods are equal) was rejected for all the dependent variables, except the EMG activity of the right latissimus dorsi. Hence, for the significant dependent variables, the alternative hypothesis was accepted. This result indicates that for all the dependent variables, excluding the right latissimus dorsi, the mean of at least one valve-opening method was significantly different than the means of the remaining methods.

The torque main effect was significant for the following dependent variables: time to open the valve, Borg-rating, and the EMG activity of the right anterior deltoid, left anterior deltoid, left trapezius, and left latissimus dorsi. In other words, the null hypothesis (Hypothesis 2: The means are equal between both torque settings) was rejected for these dependent variables. This result indicates that, for each of these dependent variables, the means of both torque settings were significantly different than each other. On the other hand, the torque main effect was not significant for the EMG activity of the right trapezius, right latissimus dorsi, right erector spinae, and left erector spinae. Hence, the null hypothesis was not rejected for these dependent variables, suggesting that the means of both torques for each of these dependent variable were equal. The raw data for the individual participants is provided in Appendix F, and the SAS programs for the ANOVA and Tukey-Kramer tests are presented in Appendix G.

CHAPTER 6: PROJECT-1 DISCUSSION

6.1 Comparison of Valve Opening Methods

This research sought to compare four different valve-opening methods at two torque levels through EMG, time measurements, and Borg-ratings. Table 59 summarizes the EMG measurements, Borg-ratings, and the recorded time to open the valve averaged over both torques (Averaging over both torques is acceptable since the interaction effect between torque and method was not significant for any of the dependent variables). The green values in the table correspond to the lowest measurements in the column (i.e. muscle, Borg, or time); whereas, the red values correspond to the highest measurements in the column. This table identifies the opening method that has relatively low EMG activities across all muscles and that is associated with a low Borg-rating and time.

Table 59: The EMG, Borg-rating, and time results, averaged over both torques (15 Nm and 30 Nm), of each opening method. The green cells represent the lowest values in the column, and the red cells represent the highest values in the column.

	Overall Averages of Maximum EMG Activities (%RC)									
Method\Muscle	R. Del	L. Del	R. Trap	L. Trap	R. Lat	L. Lat	R. ES	L. ES	Borg-rating	Time (sec)
BH	70.4	21.5	37.6	25.9	38.8	73.5	42.4	52.2	4.8	39.8
CW-R	69.9	63.1	27.8	28.2	33.6	40.0	46.1	50.3	4.4	88.5
CW-U	86.4	64.8	56.8	55.1	44.6	55.8	62.9	63.2	3.5	25.6
MW	81.2	63.2	52.4	70.2	44.9	57.2	56.9	58.4	3.0	23.1

In regards to the EMG activities, the CW-R appears to be the best method. Five of the lowest EMG activities were detected at this method – at the right anterior deltoid (69.9 %RC), right trapezius (27.8 %RC), right latissimus dorsi (33.6 %RC), left latissimus dorsi (40.0 %RC), and left erector spinae (50.3 %RC). Also, two of the remaining three muscles were associated with

EMG activities that were not significantly different than their corresponding lowest EMG activities, which were the left trapezius and right erector spinae muscles.

However, a downside to the CW-R method is that it was the least efficient method. It required an average of 88.5 s to fully open the valve, which was significantly greater than the average times of the other methods. So although this method required low muscle activations, it required the most time to fully open the valve.

In contrary to the EMG output, participants perceived CW-R to be of the most strenuous methods. It received an average Borg-rating of 4.4, which was not significantly different than the highest average Borg-rating of 4.8 for BH. In the Borg-scale, a 4.4 corresponds to a physical task that falls between “somewhat difficult” (4) and “difficult” (5). A possible explanation as to why this method received a high Borg-rating is that it involved forceful exertions for longer periods of time. The aerobic requirements to sustain forceful exertions for greater times may have influenced the Borg-ratings.

Another method that was associated with low EMG activities was the BH method. Three of the muscles received the lowest EMG activities using this method, including the left deltoid (21.5 %RC), left trapezius (25.9 %RC), and right erector spinae (42.4 %RC) muscles. Also, four of the remaining five muscles had EMG activities that did not differ significantly from their corresponding lowest EMG activities, including the right anterior deltoid (70.4 %RC), right trapezius (37.6 %RC), right latissimus dorsi (38.8 %RC), and left erector spinae (52.2 %RC). On the other hand, the left latissimus dorsi was associated with significantly higher EMG activity (62.2 %RC) in this method than all the other methods. Apart from the left latissimus dorsi, all the muscles in this method had the lowest or close to lowest EMG activities.

The BH method was associated with significantly lower times than the CW-R; yet, participants perceived BH to be the most strenuous method. It had an average Borg-rating of 4.8. All the methods except for BH involved the use of a valve-wrench, which allows the participants to exert less force in generating a torque than they would in using BHs alone. This may explain why BH was associated with the highest average Borg-rating.

The CW-U method appears to have the greatest loading on the trunk muscles than all the other methods. Five of the eight muscles received their greatest EMG activities using this method, including the right anterior deltoid (86.4 %RC), the left anterior deltoid (64.8 %RC), right trapezius (56.8 %RC), right erector spinae (62.9 %RC), and left erector spinae (63.2 %RC). The advantage of this method, however, is that it required significantly less time to fully open the valve than BH or CW-R. It required an average of only 25.6 s to fully open the valve. Another advantage of this method is that participants perceived it to be significantly less strenuous than BH and CW-R. The average Borg-rating of the CW-U method was 2.6. So although the overall EMG activities of the CW-U appeared greatest, it was perceived to be the least strenuous. This method may, in fact, be less strenuous since the high muscle activities are sustained for a relatively short period of time. A future study may investigate this matter further and compare the methods based on aerobic parameters, such as oxygen consumption and maximum heart rate. These measures will provide information on the aerobic requirements of each method, which may explain the discrepancy between the EMG results and the Borg-ratings.

In using the MW method, two muscles —left trapezius and right latissimus dorsi—were working at EMG levels significantly greater than they were in the other methods. The remaining muscles were second most active in this method. Furthermore, no significant differences were detected between them and their corresponding highest EMG activities, except for the left latissimus dorsi muscle. The EMG activity of the left latissimus dorsi while using the MW (57.2 %RC) was significantly lower than the highest EMG activity (73.5 %RC), which was found at BH. At the same time, the EMG levels at the right anterior deltoid and left erector spinae muscles were not significantly different than their corresponding lowest EMG activities. However, in all the muscles the EMG activities were closer to the highest EMG activities than they were to the lowest EMG activities.

Although the muscle activities were relatively high in the MW method, it was associated with the lowest average Borg-rating, and it was the most efficient method to use in opening the valve. In other words, participants perceived this method to require the least physical exertion. The disagreement between the EMG and Borg-rating results again may be influenced by the aerobic demands associated with each method. Since the high EMG exertions are performed for shorter times in this method than other methods, participants may have perceived it to be the least strenuous. The aerobic demands of each method may be investigated in a future study to learn more about the physiological effects associated with each method.

Since the Borg-ratings and EMG results did not match well across the different methods, it is difficult to specify one method as being ergonomically the best. According to the EMG results alone, the best method was CW-R, followed by BH, MW, and finally CW-U. However, according to the Borg-ratings, the best method was MW, followed by CW-U, CW-R, and finally BH. In terms of efficiency, the best method was MW, followed by CW-U, BH, and finally CW-R. The times and Borg-ratings seemed to have a proportional relationship, which is why it is believed that the aerobic demands associated with each method was an influencing factor in the Borg-ratings. In conclusion, this study would recommend the MW for valve-operation because although it was associated with relatively high EMG activities, the EMG activities were sustained for short periods of time and overall participants perceived it to be the least strenuous method. However, a future study may verify this conclusion by measuring the aerobic demands involved with each method.

6.2 Comparison of Torque Settings

One of the objectives of this research was to determine how the torque level (15 Nm and 30 Nm) affects the values of the dependent variables among the different valve-opening methods. For all the dependent variables, the interactions between the torque and method effects were not statistically significant (Table 58). In other word, the dependent variable trends across the different methods at both torques were not significantly different from each other.

However, the torque main effect was statistically significant for the majority of the dependent variables. Table 60 summarizes the averages of the dependent variables and their associated p-values for both torques. A highlighted p-value in the table indicates that the torque main effect was significant for the corresponding dependent variable. For all the dependent variables, the averages were higher at 30 Nm than at 15 Nm. According to Table 60, the dependent variables associated with a statistically significant torque effect included only: the EMG activities of the right anterior deltoid, left anterior deltoid, left trapezius, and left latissimus dorsi, as well as the Borg-rating and the time to open the valve; while the remaining dependent variables (EMG activities of the right trapezius, right latissimus dori, and right and left erector spinae muscles) lacked a statistically significant torque effect. This finding supports the findings of Aghazadeh et al. (2012), who investigated the same valve-opening methods at 25 Nm and 50 Nm. They found that, for the majority of the dependent variables, values were higher at 50 Nm than at 25 Nm.

In summary, the torque setting did not significantly affect the trend across the different methods for any of the dependent variables. The only effect torque had on the dependent variables was in the magnitude of their corresponding values. All values were greater at the higher torque than at the lower torque.

Table 60: The EMG, Borg-rating, and time results for 15 Nm and 30 Nm.

Torque	Overall Averages of Maximum EMG Activities (%RC)								Borg-rating	Time (sec)
	R. Del	L. Del	R. Trap	L. Trap	R. Lat	L. Lat	R. ES	L. ES		
p-value	0.0059	0.0132	0.5413	0.0365	0.5269	<.0001	0.4784	0.1136	<.0001	0.0042
30 Nm	84.6	57.8	44.8	48.4	42.5	65.2	53.0	58.8	4.9	47.5
15 Nm	69.3	48.4	42.5	41.3	38.5	48.0	51.1	53.3	3.0	40.9
Difference	15.3	9.4	2.3	7.1	4.0	17.2	1.9	5.5	1.9	6.6

6.3 Comparing Results to Aghazadeh et al. (2012)

The current research was a follow-up study to Aghazadeh et al.'s (2012) work. Aghazadeh et al. (2012) incorporated only one modification to the conventional wrench, which was the addition of a joint in the handle. The MW was compared to the same conventional opening methods of the current study, but at two different torque levels, which were 25 Nm and 50 Nm. Also, only seven muscles were considered in their study— some of which were different than the current study— including the right and left biceps and right and left medial deltoids, right and left trapezii, and right latissimus dorsi. The common muscles from both studies were three muscles: right trapezius, left trapezius, and right latissimus dorsi.

Regardless of torque, both studies found that the MW required the least time to open the valve, while the CW-R required the most time. The MW was perceived to be the least physical exerting at 15, 25, and 30 Nm, but at 50 Nm, it had almost the highest Borg-rating of approximately 7. For all the torques, BH had the highest or close to the highest average Borg-rating. This result seems valid since BH does not have the mechanical advantage that a wrench provides as is found in the other methods. The EMG results of both studies showed the CW-R method to be associated with the least overall muscle activity, but this method required significantly greater times to open the valve than the other methods. Aghazadeh et al. (2012) described the MW as requiring the second least overall muscle activation of the upper extremities and trunk at 25 Nm, but requiring the most overall muscle activation at 50 Nm. On the other hand, the current study found the MW requiring the third least overall muscle activation of the shoulders and back at both 15 Nm and 30 Nm. Due to the differences between the EMG and Borg-rating results, further research is still needed to determine the best method of opening a valve system. Future research may consider comparing the different valve-opening methods at additional torques similar to that found in the field because the torque level may have an effect on not only the magnitude of the values of the dependent variables, but also the overall preferred method.

CHAPTER 7: PROJECT-1 CONCLUSIONS

The aim of this research was to compare the ongoing development of an ergonomic valve-wrench (MW) to three conventional valve-opening methods (BH, CW-R, and CW-U), in terms of EMG measurements, Borg-ratings, and efficiency in opening a simulated valve. The method that was associated with the least overall EMG activity of the shoulder and trunk muscles was CW-R, followed by BH, MW, and finally CW-U. This study expected that methods associated with relatively high overall EMG activity to have also relatively large Borg-ratings; however, that was not the case. According to the Borg-ratings, the method that was perceived to be the least physically exerting was MW (3.0), followed by CW-U (3.5), CW-R (4.4), and finally BH (4.8). There are two possible explanations for the discrepancy between the EMG and Borg results:

- The EMG analysis was based on the maximum EMG activities detected in each trial, which does not take into account the duration at which these EMG activities were sustained. On the other hand, the Borg-ratings may have been a function of not only the maximum physical exertion but also of the time duration that exertion was endured (aerobic demand).
- The muscles of investigation in this study were limited to only trunk and shoulder muscles because injuries are more prevalent in those areas from valve-operation; however, the upper and lower extremity muscles likely have a major role in turning the handwheel and producing force, which may have influenced the Borg-rating results.

In terms of efficiency, the best method was MW (23.1 s), followed by CW-U (25.6 s), BH (39.8 s), and finally CW-R (88.5 s). The times and Borg-ratings seemed to have a proportional relationship, which is why it is believed that the aerobic demands associated with each method was an influencing factor in the Borg-ratings.

In conclusion, this study would recommend the MW for valve-operation because although it was associated with relatively high EMG activities, the EMG activities were sustained for short periods of time and overall participants perceived it to be the least strenuous method. However, a future study may verify this conclusion by measuring the aerobic demands (e.g. maximum oxygen consumption and heart rate) required with each opening method and examine how they relate to the Borg-ratings of each method. Findings from such a study may also explain the discrepancy found between the EMG and Borg results.

All the valve-opening methods in this study were performed at two different torque levels to determine whether different torques have varying effects on the dependent variables. According to the ANOVA test, the interaction effect between torque and method was not significant for any of the dependent variables. This result suggests that the torque main effect can be interpreted separately from the method main effect. Torque had a significant effect on the average Borg-ratings, time, and the EMG activity of the right anterior deltoid, left anterior deltoid, left trapezius, and left latissimus dorsi muscles. The magnitudes of these dependent variables were significantly greater at 30 Nm than at 15 Nm. From 15 Nm to 30 Nm, the dependent variable values increased by an average of 1.8 for the Borg-ratings, 6.6 s for time, 15.3 %RC for the right anterior deltoid, 9.4 %RC for the left anterior deltoid, 7.1 %RC for the left trapezius, and 17.3 % RC for the left latissimus dorsi. The ANOVA test did not detect a significant difference between 15 Nm and 30 Nm for the right erector spinae, left erector spinae, right latissimus dorsi, and right trapezius muscles. In conclusion, the torque affects the Borg-ratings, time, and the EMG activities of some of the muscles only in magnitude, to where their values are significantly higher at 30 Nm than at 15 Nm.

CHAPTER 8: PROJECT-1 LIMITATIONS AND FUTURE RESEARCH

The current research has several limitations, one of which is that participants were recruited from a student population. Many of the student participants did not have previous experience in handwheel actuation; hence, the technique utilized in turning the handwheel may have differed from the way an experienced operator would turn the handwheel. However, the benefit of using inexperienced participants can inform about how useful the MW will be among new valve-operators. Since the MW will be used specifically by valve-operators, a future study may test the MW among experienced valve operators and have them provide feedback regarding the design and usability of the tool through completing questionnaires (e.g. simple device questionnaire). The MW may also be compared to conventional opening methods in the field in terms of: discomfort ratings on shoulders, neck, back, and extremities; EMG of trunk, shoulder, and neck muscles; efficiency in opening valve systems; maximum oxygen consumption; and/or maximum heart rate. The advantage such a study is that it will examine the practicality of the MW in the field, where torques of various magnitudes can be found.

Another limitation of this study is that the different methods were compared using only one handwheel height (100 cm from the floor) and angle (0^o or horizontally-oriented). According to Wieszczyk et al. (2008), the height of a handwheel does have an effect on EMG of shoulder and back muscles in BH handwheel actuation. Hence, it is possible that the height (and angle) has an effect on the EMG activities also when using valve-wrenches. A more comprehensive experiment is needed to compare the different valve-opening methods at different handwheel heights and angles. This research will determine the best valve-opening method considering various handwheel heights and angles, and it can also determine the best height and angle for a handwheel when using valve-wrenches. As far as known, all the research that investigated different handwheel heights and angles were concerned with BH handwheel actuations – nothing yet regarding handwheel actuation using a valve-wrench.

Furthermore, participants in this study were restricted to specific postures and techniques when turning the handwheel. They were asked to keep their feet firm on the ground at approximately shoulder length apart. Depending on the opening method used, they were instructed to either have their feet aligned or the left foot in front of the right foot for additional balance. However, in the field, operators may acquire different techniques in turning handwheels, which will likely result in the activation of different muscles.

Furthermore, the measures used in this research were limited to only maximum EMG activities, Borg-ratings, and time to open a valve. Future research may compare the same opening methods using aerobic measures, such as maximum oxygen consumption and maximum heart rate. Findings from such a study will inform about the aerobic demands associated with each method and may explain the discrepancy between the EMG and Borg-rating results. The EMG analysis in the current study was based on the maximum EMG activities detected during each opening method, which does not take into account the duration at which these EMG activities were sustained. On the other hand, the Borg-ratings may have been based not only on the maximum physical exertion during the trials but also on the sustained continuous effort. Future research may measure the aerobic demands required with each opening method and examine how they relate to the Borg-ratings of each method. Findings from that study may clarify why the methods in this study associated with low EMG activities received higher Borg-ratings.

During the experiments, several participants commented that the joint or hinge in the MW was unstable. Participants found it difficult to maintain a 90^{o} joint angle on the handle of the wrench as they were turning the handwheel. To address this issue, a locking joint may be incorporated in the MW design. The locking joint will allow the handle to be fixed at different angles. A prototype of this design has been developed and is shown in Figure 37. By loosening the allen screw at the joint, the handle can be adjusted between 90^{o}, 0^{o}, and -90^{o}. To fix the handle at any of these angles, the allen screw must be tightened again. The advantage of this design is that the wrench can be used as the MW by setting the joint angle to 90^{o} or as a CW by setting the angle to 0^{o}. A future research may compare the effects of the new design to other valve-opening methods using the same measures of this study and/or other measures, such as usability and aerobic measures.

Figure 37: A prototype of the modified wrench that includes a locking joint using an allen screw.

In summary, the following research are recommended for future work:

- Compare BH, CW-R, CW-U, and MW among experienced valve operators, rather than college students, using various measures, such as EMG, Borg-rating, and time measurements.
- Test the applicability of the MW in the field, where torque demands are much higher than those in a controlled lab study, and administer questionnaires regarding the design and usability (e.g. simple device questionnaire) of the MW to valve-operators. The MW may also be compared to conventional opening methods in the field using the same measures in this study (i.e. EMG, Borg-rating, and time measurements).
- Compare the different valve-opening methods at different handwheel heights and angles.
- Include other measures in comparing the different valve-opening methods, such as maximum oxygen consumption, maximum heart rate, and discomfort ratings on the shoulders, neck, back, and upper extremities;
- Evaluate the new modified wrench with the locking joint (Figure 37) with respect to conventional valve-opening methods using the same measures of this study and/or other measures, such as usability and aerobic measures.

This project contributes to the on-going research of the development of an ergonomic wrench for valve-operation. We incorporated ergonomic modifications to the valve wrench, in addition to the modification found in Aghazadeh et al.'s (2012) research. According to the results, participants perceived the new MW to be the least physically demanding and most efficient at 15 Nm and 30 Nm relative to conventional valve-opening methods. However, future research, such as the ones listed above, is still necessary to learn about the benefits and downsides associated with this wrench and how it can be further improved in design.

PROJECT-2: THE DETERMINATION OF OPERATORS' TORQUE PRODUCTION CAPABILITES AND THE OPTIMAL HANDWHEEL HEIGHT AND ANGLE

CHAPTER 9: PROJECT-2 METHODS

Project-2 compared the effects of handwheel height and angle on torque production and the muscle activities of shoulder and trunk muscles to determine an optimal handwheel position for valve-operations. Four heights (knee, elbow, shoulder, and overhead levels) and three angles (0^o, 45^o, and 90^o) were considered in this project. The torque data collected was also used to recommend maximal acceptable torque limits for handwheel-valves, accommodating most of the population's physical strength.

9.1 Participants

The sample size needed to estimate the mean torque production capabilities of the population was calculated using the method found in Machin et al. (1997). The calculations performed were based on preliminary data of ten male and ten female participants. To create a 95% confidence interval with a margin of error of ± 5 ft-lb, a sample size of 21 was needed for males and 15 for females. However, according to the literature, a sample size of 30 is enough to estimate a population mean (Hogg and Tanis, 2005). Since the literature sample size was greater than the calculated sample sizes for males and females, this study used thirty male and thirty female participants. The age range was 18 to 37 years for the males and 19 to 36 years for the females. Table 61 summarizes the demographic information of the participants. The average age, height, and weight of the male participants were 23.4 years, 177.5 cm, and 78.4 kg, respectively. The average age, height, and weight of the female participants were 24.2 years, 165.4 cm and 68.6 kg, respectively. Participants were primarily graduate or undergraduate students from the LSU population.

Table 61: Participants' demographic information in static project without EMG measurement.

	Avg (S.D.)		
	30 Males	30 Females	60 Total
Age (year)	23.4 (3.8)	24.2 (4.3)	23.8 (4.0)
Height (cm)	177.5 (5.1)	165.4 (6.9)	171.5 (8.6)
Weight (kg)	78.4 (9.8)	61.6 (12.6)	68.6 (14.2)

A power analysis was performed to determine whether the chosen sample size has sufficient power to detect differences in the means. The power was at least 92.1% for all main effects and interaction effects, which satisfies the conventional desired power of at least 80% (Cohen, 1988). The details of the power analysis are provided in Appendix A. Participants were selected and screened for health problems using the same procedure as in Project-1 (Section 4.1).

For the EMG part of this project, a total of fifteen male participants were tested, similar to project-1. Their demographic information is summarized in Table 62. The average age of the participants was 22.9 year with a range of 18 to 30 year. The average height and weight of these participants were 175.8 cm and 76.4 kg, respectively.

Table 62: Participants' demographic information in static project with EMG measurement (male participants only).

15 Males	Avg (S.D.)	Range
Age (year)	22.9 (3.4)	18 - 30
Height (cm)	175.8 (4.8)	163-183
Weight (kg)	76.4 (7.3)	59-86

9.2 Equipment

9.2.1 Handwheel

A 37.4 cm diameter handwheel was used to simulate a handwheel-valve system (Figure 38). The wheel rim is made of metal stock and is rectangular in shape with rounded edges. The height of the rim is 1.65 cm and the width is 2 cm. The handwheel also has a post, which the participants were not allowed to use during the static torque exertions.

Figure 38: A 37.4 cm diameter handwheel.

9.2.2 Isometric Strength Testing Equipment

An isometric strength testing equipment (Prototype Design and Fabrication Company, Ann Arbor, MI, USA) was used to adjust the handwheel height and angle (Figure 39). The equipment consists of a horizontal lever arm and a vertical post. The lever arm is assembled on a vertical post, such that it can be moved along the vertical post and clamped at any desired height (Figure 40). The handwheel is attached to the end of the lever arm. The lever arm has 5 holes in a semicircular fashion for adjusting the angle of the handwheel. By placing a pin through one of the holes, the handwheel angle can be fixed (Figure 41). Hence, the orientation of the handwheel can be adjusted to five different planes.

Figure 39: Isometric strength testing equipment (Prototype Design and Fabrication Company, Ann Arbor, MI, USA).

Figure 40: The lever arm can be moved along the vertical post and clamped at any desired height.

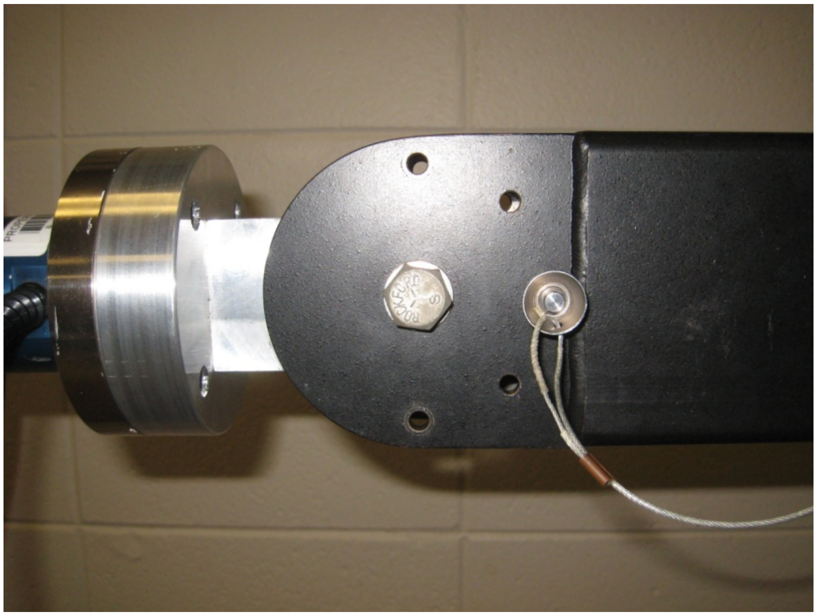


Figure 41: The lever arm has 5 holes in a semicircular fashion for adjusting the angle of the handwheel.

The lever arm of the vertical post is limited to how far it can be raised, making it difficult to simulate valve-operations at overhead height for tall participants. This limitation was addressed by elevating the entire platform of the isometric strength testing equipment, as shown in Figure 42. Two boxes were built: one box (122 cm × 92 cm × 46 cm) was placed under the platform and a second box (183 cm × 102 cm × 56 cm) was placed in front of the platform. Simulating valve-operations at knee, elbow, and shoulder height were performed by having the second box placed in front of the platform (Figure 42a). However, to simulate valve-operations at overhead height, especially for tall participants, the second box was removed; this increased the height of the handwheel from the participant allowing the simulation of overhead height (Figure 42b).

(a) (b)

Figure 42: (a) Box present in front of the platform to simulate valve-operation at knee, elbow, and shoulder height; (b) box removed to simulate valve-operation at overhead height.

9.2.3 Transducer and Torque Meter

The handwheel sits on a Mountz BMX 500F reaction style transducer (Figure 43), which measures the static torque exertions on the handwheel. It's capable of measuring torques up to 667 Nm. The output of the transducer is recorded and displayed on a Mountz Torquemate 2000 (Mountz Inc., San Jose, CA) (Figure 44). This equipment is capable of recording instantaneous, peak, and first peak torques during exertions. The difference between "peak" and "first peak" modes is that peak mode displays the highest peak torque applied, while first peak mode displays the first peak torque applied and disregards any further input. This study used the peak mode in measuring torque exertions.

Figure 43: A Mountz BMX 500F reaction style transducer.

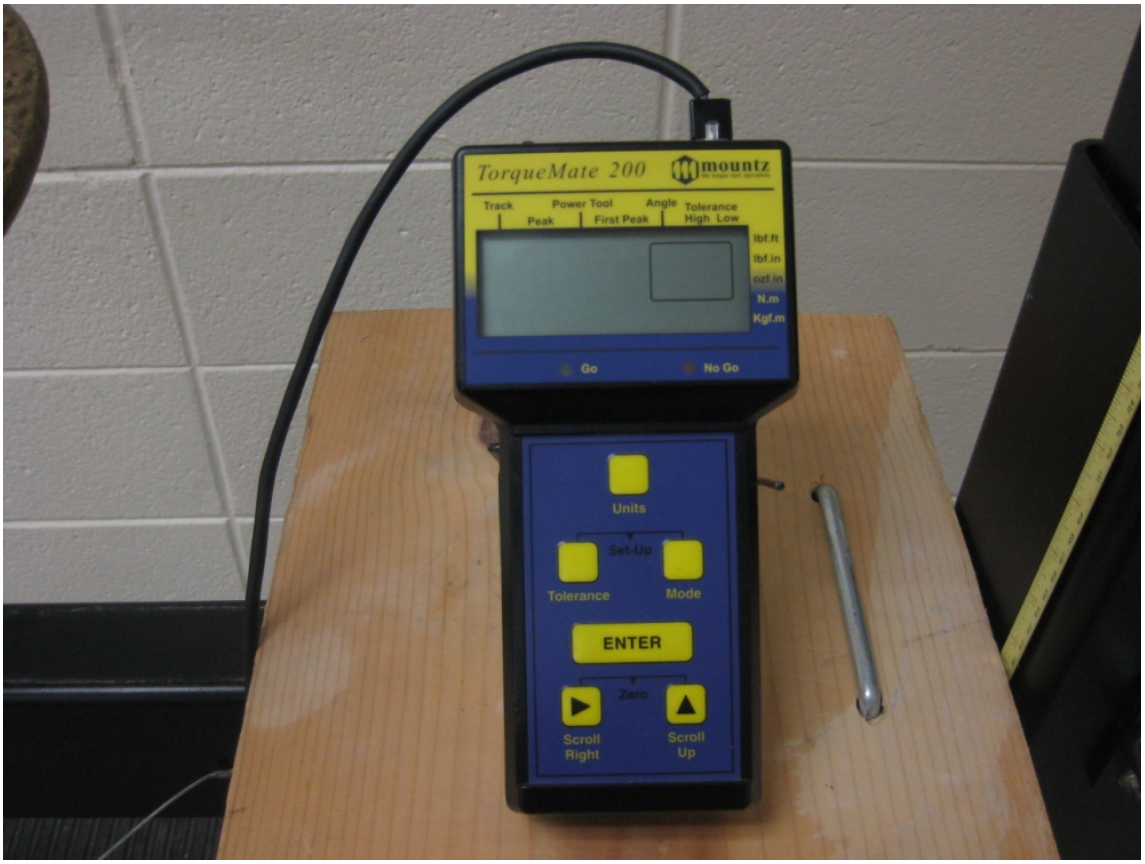


Figure 44: Mountz Torquemate 2000 for measuring torque exertions.

9.2.4 Electromyography (EMG) System

The EMG system is discussed in Section 4.2.3.

9.3 Experimental Task

Each participant performed maximum isometric torque exertions on a handwheel at various heights and angles. Participants always 'opened' the valve; thus, torque was exerted in a counterclockwise direction. This study defined handwheel height as the distance from the floor to the center of the handwheel. The various heights in this study were set with respect to each participant's anthropometry, rather than being fixed heights. This is believed to be a more appropriate analysis of handwheel heights. For instance, consider a fixed height of 110 cm; this level may be the elbow height of one person but the waist height of a taller person. The height difference of the two participants may have an effect on interpreting the data. To eliminate this confounding effect, this research used handwheel heights with respect to participants' anthropometry. The different heights that were evaluated in this study are:

- Overhead height: The height of the center of the handwheel when the participant had the left upper extremity approximately straight with a shoulder flexion of 135° (Wieszczyk et al., 2009), while also grasping the handwheel with the left hand at 135° from the centerline of the handwheel and the right hand at 315° (or -45°) (Hoff, 2000) (Figure 45).
- Shoulder height: Center of handwheel at acromion height (Figure 46). Participants had to stand in a normal upright posture for this height.
- Elbow height: Center of handwheel at elbow height (Figure 47). Participants had to stand in a normal upright posture for this height.
- Knee height: Center of handwheel at patella height (Figure 48). Participants had to squat and bend their trunk forward for this height, where the knee and back were each bent approximately 45° (Wieszczyk et al., 2009).

The handwheel angles that were evaluated in this study were:

- 90° (vertical): Handwheel was vertically-oriented (Figure 49a).
- 45° (slanted): Handwheel was set in a slanted orientation at a 45° angle from the horizontal (Figure 49b).
- 0° (horizontal): Handwheel was horizontally-oriented (Figure 49c).

Figure 45: Overhead height

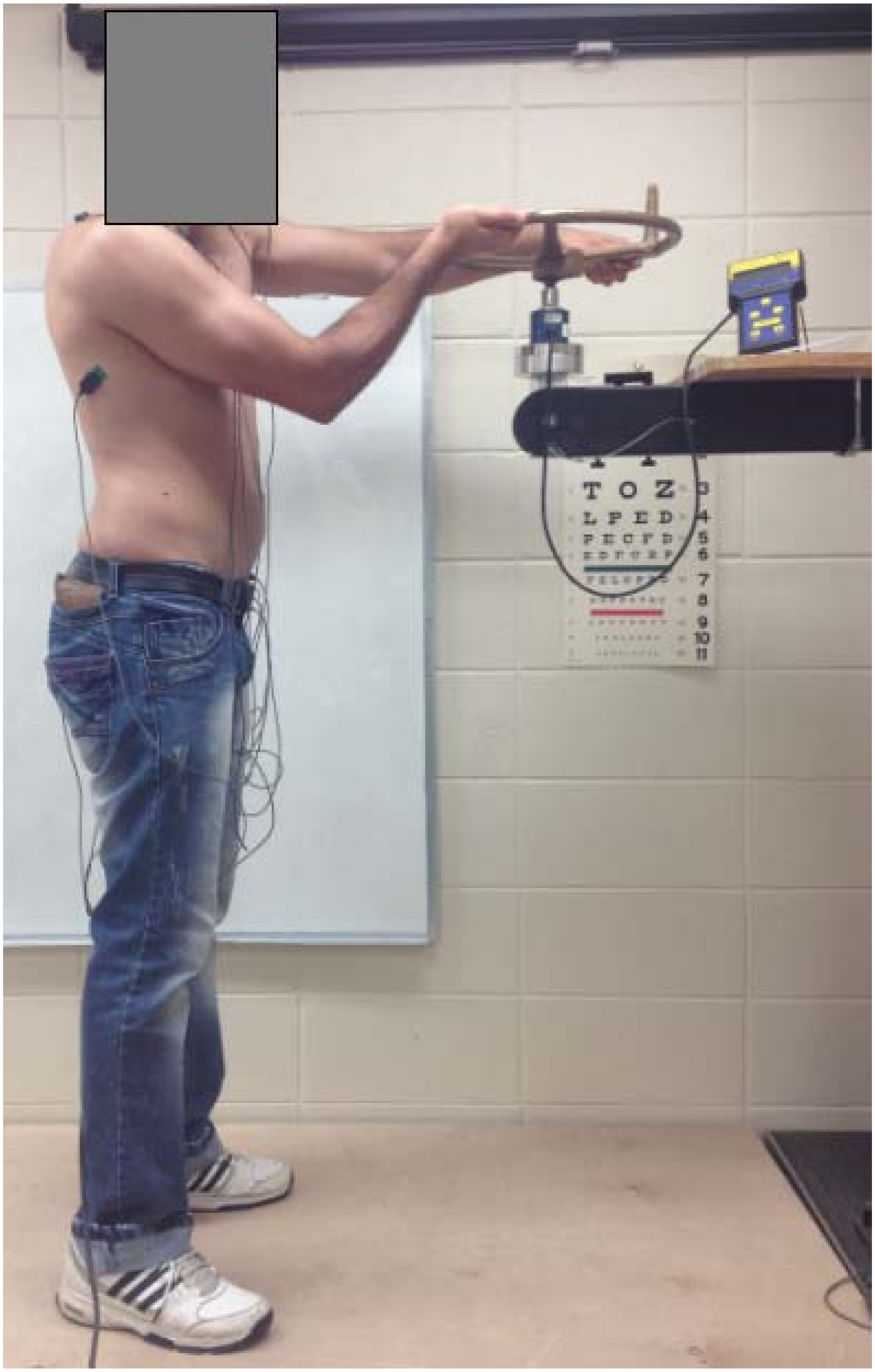


Figure 46: Shoulder height

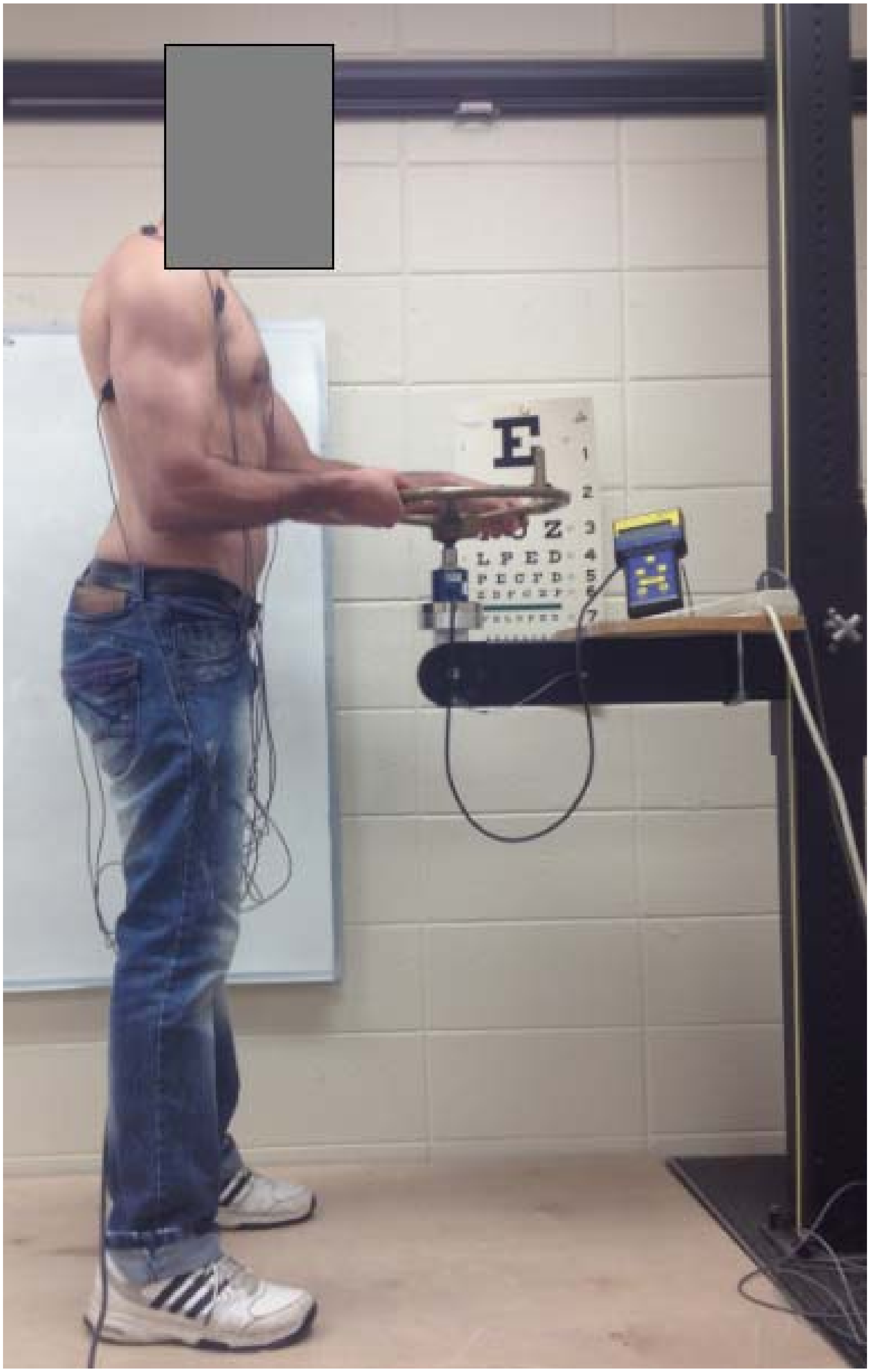


Figure 47: Elbow Height

Figure 48: Knee height.

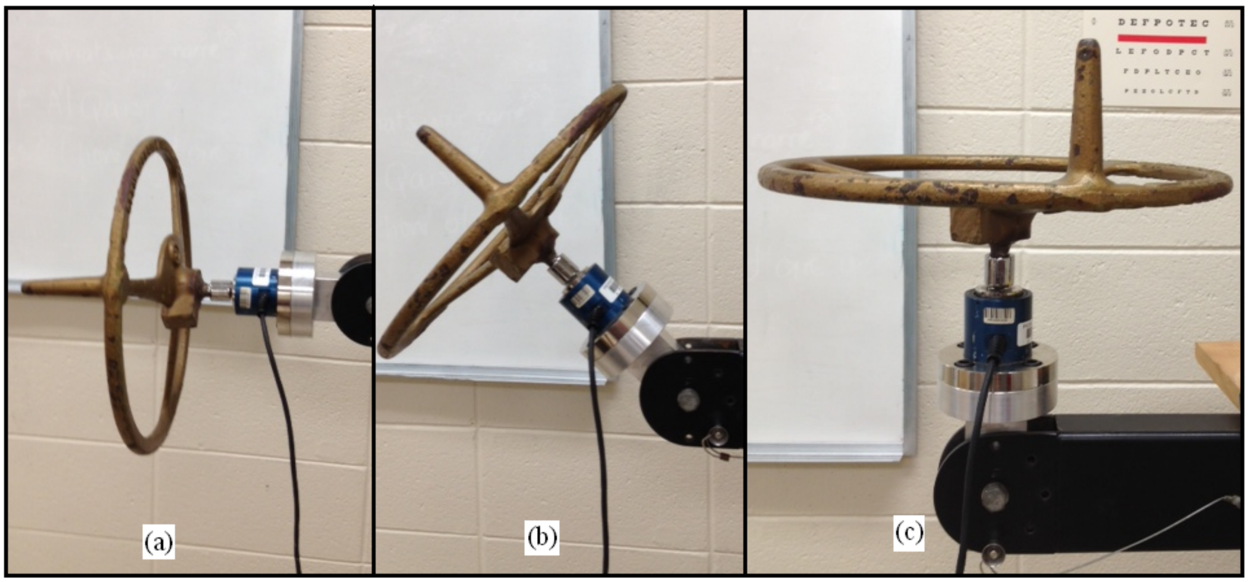


Figure 49: Handwheel angles (a) vertical orientation or 90°; slanted angle or 45°; and horizontal orientation or 0°.

9.4 Experimental Design

The dependent variables of this study were the maximum isometric torque exertion and the maximum normalized EMG activities of the right and left anterior deltoids, trapezii, latissimi dorsi, and erector spinae muscles. Two different experimental designs were developed for the maximum torque data and EMG data because the maximum torque data included a gender factor (30 male and 30 female participants), while the EMG data considered only males (15 male participants).

For analyzing the maximum torque data, a three factor split-plot experimental design was used. Unlike project 1, this project included gender as a factor of interest. Participants and gender served as blocks within which experimental conditions were randomized. The independent variables were handwheel height (knee, elbow, shoulder, and overhead), handwheel angle (0°, 45°, and 90°), and gender. Each participant performed a total of 36 (4 heights × 3 angles × 3 repetitions) trials. The 36 trials were divided into four sets of nine trials, and height was randomized to the sets. Within each height or set, the trials were further divided into three subsets of three trials (repetitions), and angle was randomized to the subsets. Height served as the whole-plot treatment and angle as the sub-plot treatment. An average maximum torque was computed for each subset of three repetitions. These averages were used in the data analysis of the maximum torque data. Figure 50 illustrates an example of how the experimental design was applied to the trials. Each small square in the figure represents one subset of three trials or repetitions, and each row represents one set of nine trials. First, the various heights were randomized to the rows, and then the angles were randomized to the small squares within each row. Each small square involved three repetitions of maximal isometric torque exertions, which were then averaged.

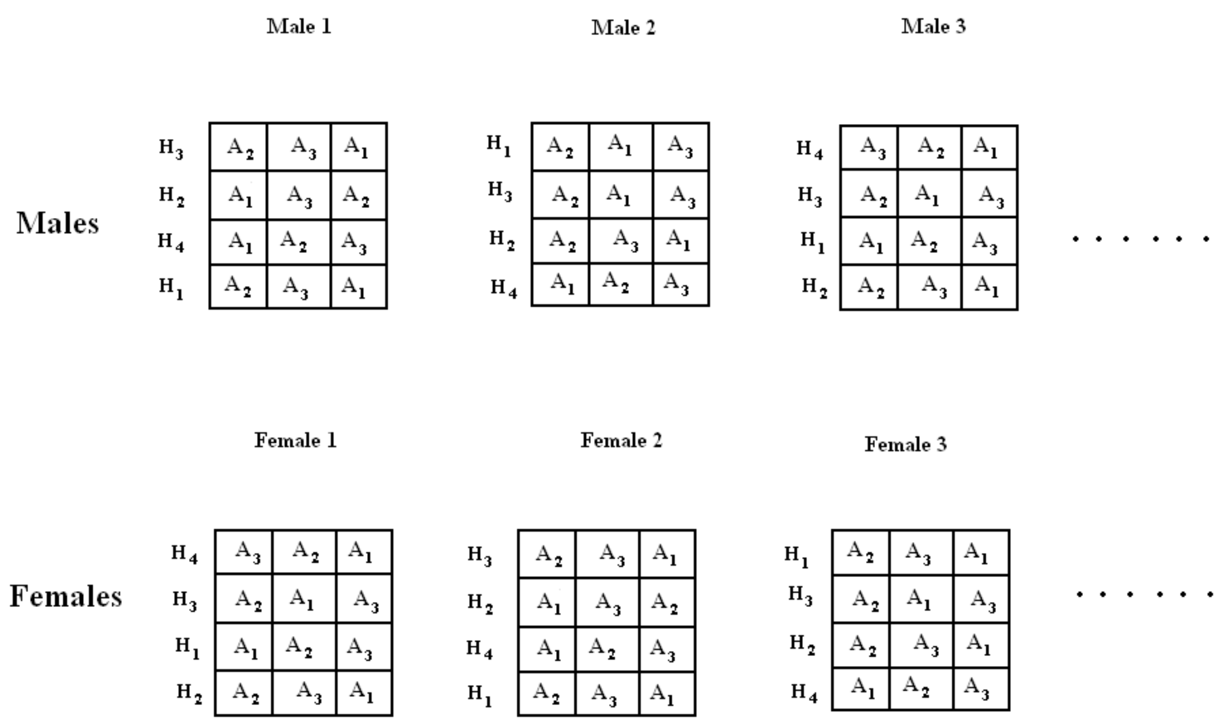


Figure 50: Split-plot design where participants and gender served as blocks, height (H) as the whole-plot treatment, and angle (A) as the sub-plot treatment.

The means model for project-2 including the gender factor was as follows:

$$y_{S2} = \mu_{G,H,A} + \rho_P + \omega_{S1} + \varepsilon_{S2} \tag{2}$$

Where:

- y_{S2}: is the average maximum torque exertion that was measured in a subset ($S2$) of three repetitions;
- $\mu_{G,H,A}$: is the fixed effect term due to gender (G), height (H), and angle (A), representing the population average;
- ρ_P: is the random term due to participant (P);
- ω_{S1}: is the random term due to set ($S1$);
- ε_{S2}: is the random term due to subset ($S2$).

For the EMG part of this project, gender was not a factor in the analysis (all participants were males), and therefore, a two factor split-plot experimental design was used. Participants served as blocks within which experimental conditions were randomized. The independent variables for this analysis were only handwheel height (knee, elbow, shoulder, and overhead) and angle (0^o, 45^o, and 90^o). Each participant performed a total of 12 (4 heights × 3 angles) trials. The 12 trials were divided into four sets of three trials, and height was randomized to the sets. Within each height or set, angle was randomized to the trials. Height served as the whole-plot treatment and angle as the sub-plot treatment. The means model for the EMG analysis of each muscle was as follows:

$$y_{Tr} = \mu_{H,A} + \rho_P + \omega_S + \varepsilon_{Tr} \tag{3}$$

Where:

- y_{Tr}: is the response or dependent variable that was measured in each trial (Tr), which in this study was the normalized EMG activity of any one muscle (i.e. right anterior deltoid, left anterior deltoid, right trapezius, left trapezius, right latissimus dorsi, left latissimus dorsi, right erector spinae, or left erector spinae);
- $\mu_{H,A}$: is the fixed effect term due to height (H) and angle (A), representing the population average;
- ρ_P: is the random term due to participant (P);
- ω_S: is the random term due to the set of three trials (S);
- ε_{Tr}: is the random term to trial (Tr).

9.5 Research Hypotheses

For each dependent variable (i.e. maximum isometric torque exertion, and the normalized EMG activity of each of the eight muscles investigated), the following hypotheses were tested:

- Hypothesis 1 for Height Main Effect
    - H_0: The means of all the handwheel heights are equal.
    - H_1: The mean of at least one handwheel height is significantly different than the remaining means.
- Hypothesis 2 for Angle Main Effect
    - H_0: The means of all the handwheel angles are equal.
    - H_1: The mean of at least one handwheel angle is significantly different than the remaining means.

- Hypothesis 3 for Height and Angle Interaction Effect
  - H_0: There is no significant interaction between the height and angle effects.
  - H_1: There is a significant interaction between the height and angle effects.

Since gender was a factor in the analysis of the maximum isometric torque exertions, the following hypotheses were additionally tested for that dependent variable:

- Hypothesis 4 for Gender Main Effect
  - H_0: The means are equal between males and females.
  - H_1: The means between males and females are significantly different than each other.
- Hypothesis 5 for Gender and Height Interaction Effect
  - H_0: There is no significant interaction between the gender and height effects.
  - H_1: There is a significant interaction between the gender and height effects.
- Hypothesis 6 for Gender and Angle Interaction Effect
  - H_0: There is no significant interaction between the gender and angle effects.
  - H_1: There is a significant interaction between the gender and angle effects.
- Hypothesis 7 for Gender, Height, and Angle Interaction Effect
  - H_0: There is no significant interaction between the gender, height, and angle effects.
  - H_1: There is a significant interaction between the gender, height, and angle effects.

9.6 Data Collection and Processing

Each participant was given an orientation, introducing them to the equipment, data collection procedures, and specifics of the experimental tasks. After the orientation, they were asked to sign the IRB form. Their demographic (age, height, weight, and gender) information was recorded.

Then the participants went through a five-minute warm-up session on a treadmill (Nautilus T914 Commercial Series, Nautilus, Inc. Global Headquarters 16400 SE Nautilus Drive Vancouver, WA 98683). The speed of the treadmill was adjusted by the participants to their comfortable walking speed (3 miles per hour).

Subsequent to the warm-up session, preparations were carried out to get the participants ready for EMG data acquisition. Any hair on the skin at the right and left anterior deltoids, right and left trapezii, right and left latissimi dorsi, and right and left erector spinae muscles were removed. Also, the same areas were cleaned with alcohol. Then the EMG surface electrodes were attached to the muscles of interest. The exact electrode locations were already discussed in Section 4.6.2 (Figure 10). After attaching the electrodes, participants performed a test contraction for each muscle pair to ensure good electrode-skin contact.

Participants performed the same series of RC exertions as discussed in Section 4.6.3. The maximum EMG activities in the RC exertions were used for normalizing the EMG data collected from the experimental trials. Following the RC measurements, the participants performed maximum isometric torque exertions on a handwheel at four different heights and at three different angles (The experimental task was discussed more in detail in Section 9.3). Hence, there were a total of 12 height-angle combinations, and they were randomized to the trials. The participants had to stand with feet firm on the ground at approximately shoulder length apart. They were instructed to grasp the handwheel with the left hand at 135^{o} from the centerline of the handwheel and the right hand at -45° (or 315°) (Figure 51) (Hoff, 2000). They were told to steadily increase their torque output to their maximum level in 3 to 5 seconds, hold it for 3 seconds, and gradually decrease the force in 3 seconds (Konrad, 2005). At each height and angle, three exertions were performed and recorded (Appendix E). In case of variability greater than 10% between trials, a fourth trial was performed and the average of the best three values was computed. For each height and angle combination, EMG activities were measured for a period of 10 seconds, giving participants enough time to reach their maximum exertion. To avoid muscular fatigue, repetitions were separated by 30 to 60 seconds of rest (Konrad, 2005) and sets were separated by 2 minutes of rest (Caldwell et al., 1974; Sparto et al., 1997; Hummel et al., 2005; Andersen et al., 2008).

Figure 51: Hand placement locations during maximal isometric torque exertions.

Similar to project-1, the raw EMG activity from each electrode location was demeaned first and then full-wave rectified. The full wave rectified EMG activity was then low pass filtered at 4 Hz, using a fourth-order dual pass Butterworth digital filter, to form a linear envelope (Burnett et al., 2007). The peak activation of each muscle in each trial was normalized with respect to the maximum EMG activity of its corresponding RC exertion. Therefore, results for each muscle are reported as a percentage of the muscle's RC.

9.7 Statistical Analysis

A three factor split-plot analysis of variance (ANOVA) was used to assess the effects of gender, handwheel height, and handwheel angle on the maximum torque exertions; and a two factor split-plot ANOVA was used to assess the effects of handwheel height and angle on the normalized EMG activity. For all significant effects, post hoc analyses, in the form of Tukey multiple pairwise comparisons (Honestly Significant Difference [HSD]), were performed to determine the source(s) of the significant effect(s). The significance level (α) was set at 5%. Statistical significance was based on calculated p-values.

9.8 Calculation of Recommended Torque Limits

The average torque data collected in this study was used to compute maximum recommended torques for handwheel-valve systems. When designing any system that involves forceful exertions, the general principle in ergonomics is to choose a force that is within the capabilities of most of the population. Most of the population in this context generally refers to 95% of females. To accommodate 95% of the female population in valve-operations, this study computed the 5^{th} percentile values from the maximum torque exertion data of the female participants in this study (Attwood et. al., 2002). This accommodation is only limited to single isometric torque exertions on a handwheel. However, in the field, operators are expected to repetitively turn a handwheel until the valve is fully closed or open, which can take up to 15 minutes (Jackson et al., 1992). Also, sometimes operators are required to open/close several valves. In such cases, the recommended demands or torque limits should be lower than the maximum strength for single efforts.

To address this issue, Potvin (2012a) developed an equation that uses information on task frequency and effort duration to estimate maximum acceptable efforts (MAE) for repetitive tasks. He attempted to fit an equation to empirical psychophysical data from 69 studies, in much the same way that the widely-used National Institute for Occupational Safety and Health (NIOSH) lifting equation was fit to data of a variety of lifting psychophysical capacities (Waters et al., 1993). The only dependent variable asked for in the equation is duty cycle (DC), which is the percentage of time an individual is engaged in effort (DC = [frequency of effort]*[duration of each effort]/[cycle time]). After computing a DC for a particular task, one can input the DC value into the following equation to estimate an MAE for the task:

$$MAE = 1 - \left[DC - \frac{1}{28{,}000}\right]^{0.24} \tag{4}$$

Where:

- MAE: is the maximum acceptable effort reported as a percentage;
- DC: is the duty cycle

The maximum acceptable effort (MAE) computed from the equation is a percentage of the average maximum force (i.e. strength) from a maximum voluntary effort (MVE) for a task. To determine the recommended maximum acceptable force (MAF) or torque (MAT) for the task, Potvin (2012a) advised multiplying MAE by the average MVE associated with that task. For a single exertion, the acceptable force should be a value that accommodates most of the population. This value has generally been accepted to be as the 5th percentile value of females.

Therefore, to compute an MAF or MAT, this study recommends multiplying MAE with the 5th percentile strength value of females, instead of the average strength value.

Potvin's (2012b) equation demonstrated strong predictive capabilities for a wide-range of tasks, including wrist torques, forearm torques, arm exertion forces, lifting, and lowering tasks. Across 111 combined upper extremity and manual materials handling tasks, the equation predicted MAE well with an explained variance of 91.4% ($r^2 = 0.914$) and a root mean square (RMS) error of 6.7% of MVE. Furthermore, Potvin (2012a) found the relationship between DC and MVE to be quite robust, regardless of how the frequency and duration multiplied into DC.

Since this equation proved to be applicable to a wide-variety of tasks, this study utilized it to recommend MAT for continuous handwheel-valve operations. MATs were computed by multiplying MAE with the 5th percentile value of the females' maximum torque exertions in this study. Mathematically, this can be expressed as follows:

$$MAT_{ij} = T_{ij} * MAE = T_{ij} * \left(1 - \left[DC - \frac{1}{28{,}800}\right]^{0.24}\right) \tag{5}$$

Where:

- MAT: is the recommended maximum acceptable torque for continuous actuation of a handwheel at height i and angle j;
- T_{ij}: is the 5th percentile value of the females' maximum torque exertions at handwheel height i and angle j;

CHAPTER 10: PROJECT-2 RESULTS

10.1 Maximum Isometric Torque Exertions

Figure 52 presents a graph of the average maximum isometric torque exertions of the participants at each handwheel height (overhead, shoulder, knee, and elbow) and angle (0^o, 45^o, and 90^o) combination. From the graph, it can be seen that the height associated with the highest torque exertion depends on the angle level being analyzed, and vice versa. For instance, at 45^o the height level and the maximum torque exertions have a positive relationship, while at 0^o they have an inverse relationship. This finding is supported by the ANOVA test (Table 63), which found the interaction effect between height and angle to be significant with a p-value less than 0.0001. Therefore, each specific height-angle combination needs to be considered in the analysis.

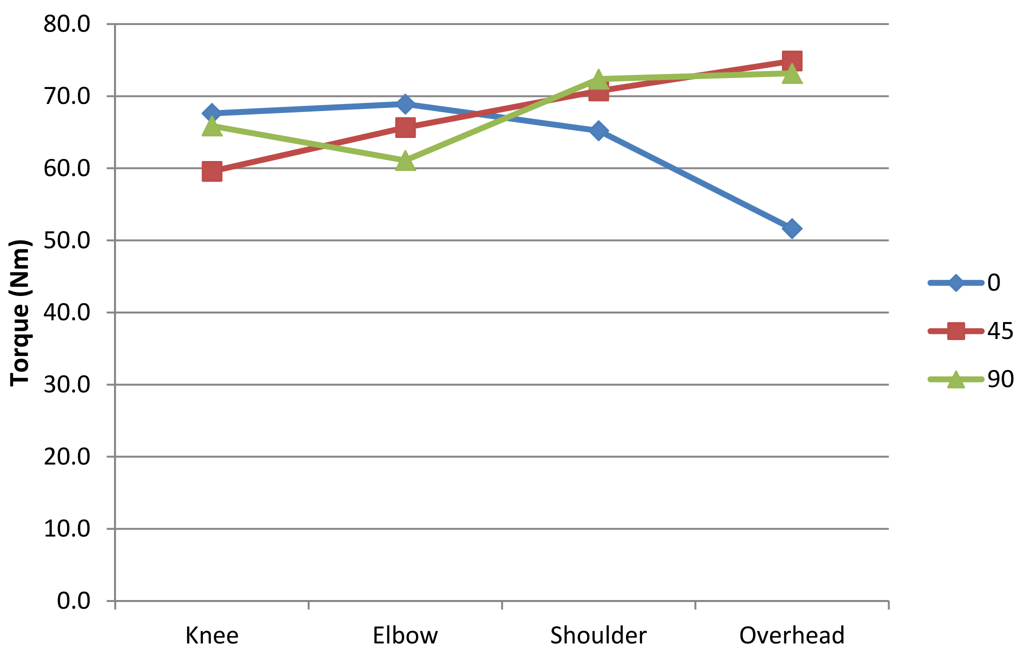


Figure 52: The average maximum isometric torque exertions associated with each handwheel height-angle combination.

Table 63: ANOVA results for the average maximum torque exertion. A highlighted p-value indicates that the corresponding effect is significant.

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
G	1	58	87.28	<.0001
H	3	174	6.91	0.0002
G*H	3	174	1.12	0.3444
A	2	464	25.87	<.0001
G*A	2	464	7.33	0.0007
H*A	6	464	57.23	<.0001
G*H*A	6	464	1.57	0.1535

Table 64 summarizes the average maximum torque exertions and the standard deviations associated with each handwheel height-angle combination. Since the height-angle interaction effect was significant, a Tukey test was performed to determine the sources of the statistical significance in the interaction. Table 65 presents the Tukey results, grouping handwheel height-angle combinations into different letter groups. Handwheel positions in the same letter group indicate that no significant difference exists between them in the average maximum torque exertion; while handwheel positions in different letter groups indicate that significant differences exists between them in the average maximum torque exertions. The handwheel position associated with the highest maximum torque exertion was found at overhead 45^{o} (74.9 Nm). Other height-angle combinations that were not significantly different from overhead 45^{o} were overhead 90^{o} (73.2 Nm), shoulder 90^{o} (72.4 Nm), and shoulder 45^{o} (70.7 Nm), since they all fell in the same letter group A. The lowest maximum torque exertion was found at overhead 0^{o}, which had an average torque of 51.6 Nm. This handwheel height and angle was found to be significantly lower than all the other handwheel positions.

Table 64: The average maximum torque exertion and standard deviation associated with each handwheel height-angle combination.

Maximum Torque Exertions (Nm)			
Height	Angle	Average	S.D.
Overhead	90	73.2	20.2
	45	74.9	22.1
	0	51.6	16.2
Shoulder	90	72.4	20.8
	45	70.7	22.0
	0	65.2	19.5
Elbow	90	61.1	17.1
	45	65.7	19.3
	0	68.9	21.7
Knee	90	65.9	18.9
	45	59.6	17.3
	0	67.6	23.6

Table 65: Tukey-Kramer output of the average maximum torque exertions for the interaction effect of handwheel height (H) and angle (A).

H	**A**	**Estimate**	**Letter Group**						
Ov	45	74.9	A						
Ov	90	73.2	A	B					
Sh	90	72.4	A	B					
Sh	45	70.7	A	B	C				
El	0	68.9		B	C	D			
Kn	0	67.6		B	C	D			
Kn	90	65.9			C	D	E		
El	45	65.7			C	D	E		
Sh	0	65.2				D	E		
El	90	61.1					E	F	
Kn	45	59.6						F	
Ov	0	51.6							G

Another interaction effect that yielded a significant p-value was between gender and angle ($p = 0.0007$). Table 66 summarizes the average maximum torque exertions and standard deviations associated with each gender-angle combination. Table 67 presents the Tukey output for this interaction to determine the sources of the statistical significance(s). The male participants exerted significantly higher torques at 90° (91.0 Nm) and 45° (89.9 Nm) oriented handwheels than at 0° (83.5 Nm). The female participants produced approximately equal torques across the different angles with the average torque exertions ranging between 45.5 Nm and 43.2 Nm.

Table 66: The average maximum torque exertion and standard deviation associated with each gender-angle combination.

Maximum Torque Exertions (Nm)			
Gender	Angle	Average	S.D.
Male	90	91.0	23.2
	45	89.9	24.1
	0	83.5	24.4
Female	90	45.3	14.4
	45	45.5	15.5
	0	43.2	15.4

Table 67: Tukey-Kramer output of the average maximum torque exertions for the interaction effect between gender (G) and angle (A).

G	**A**	**Estimate**	**Letter Group**		
M	90	91.0	A		
M	45	89.9	A		
M	0	83.5		B	
F	45	45.5			C
F	90	45.3			C
F	0	43.2			C

Regardless of angle, the male participants produced significantly higher torque exertions than the female participants ($p < 0.0001$). The average torque exertion for each gender was 88.1 Nm and 44.7 Nm, respectively. The strength capabilities of the males were almost twice that of the females.

10.2 Maximum Recommended Torque Limits

The average torque data collected in this study was used to compute maximum recommended torques for handwheel-valve systems. First, the 5th percentile torque strength values of the female participants were calculated. Since the interaction effect between handwheel height and angle was significant, calculating one overall torque average to represent all the heights and angles would be misleading. Therefore, the torque percentile values were calculated for each handwheel height and angle combination (Table 68). The 5th percentile values ranged between 13.7 Nm and 24.1 Nm, depending on the height and angle of the handwheel. These percentile values may be thought of as maximum recommended torque limits for the cracking torque or a single torque exertion on a handwheel. Ultimately, the selection of the appropriate torque limit will depend on the height and angle of the handwheel that is being designed.

Table 68: Maximum recommended torque limits calculated as the 5th percentile values of the female participants' maximum isometric torque exertions at the various handwheel heights and angles.

Height	Angle	Isometric Torque (Nm)
		5th percentile (females)
Overhead	90	23.9
	45	22.9
	0	13.7
Shoulder	90	19.5
	45	19.3
	0	19.6
Elbow	90	21.8
	45	20.8
	0	22.3
Knee	90	24.1
	45	20.1
	0	19.8

Table 68 summarizes recommended maximum torque limits for single exertions in valve operations. However, if an operator is expected to repetitively turn several handwheels per day, which is likely the case for a plant operator, then the torque demands should be even less than the acceptable strength for single exertions. This study utilized Potvin's (2012a) equation to estimate MAE as a function of DC or the percentage of time an individual is engaged in effort. Calculated MAEs were multiplied by the 5th percentile torque strength values to compute MATs. Figure 53 shows a graph of recommended MATs for the different heights and angles investigated in this study as a function of duty cycle. The twelve lines in the graph correspond to the twelve height-angle combinations that were investigated in this study. This equation assumes that for a one second exertion, which is equivalent to a DC of 0.0000347 (DC = 1 s / 8 hr = 1 s / 28,800 s = 0.0000347), the MAE will be equal to 100% of the 5th percentile torque value of the female participants. However, as DC increases, the MAE percentage will decrease exponentially.

To determine a MAT for any plant, one must first identify the handwheel height and angle in consideration and also estimate the duty cycle. The duty cycle will depend on the average number of valves required to be opened/closed per day and how long it takes to open/close each valve. For illustration, consider a job that involves opening only one valve per day (8-hour shift) and that the average time required to open the valve with a handwheel at elbow 0^{o} is two minutes. In this case, DC will be equal to 0.004167 (= 2 min / 8 hr = 120 s / 28,800 s), resulting in an MAE of 0.732 or 73.2%. In other words, by increasing the duration of the task from one second to two minutes, the MAE decreases by approximately 26.8%. The MAE is then multiplied by the 5th percentile value associated with that handwheel height and angle from Table 68 (22.3 Nm). The resulting MAT for operating a handwheel at elbow 0^{o} for two minutes

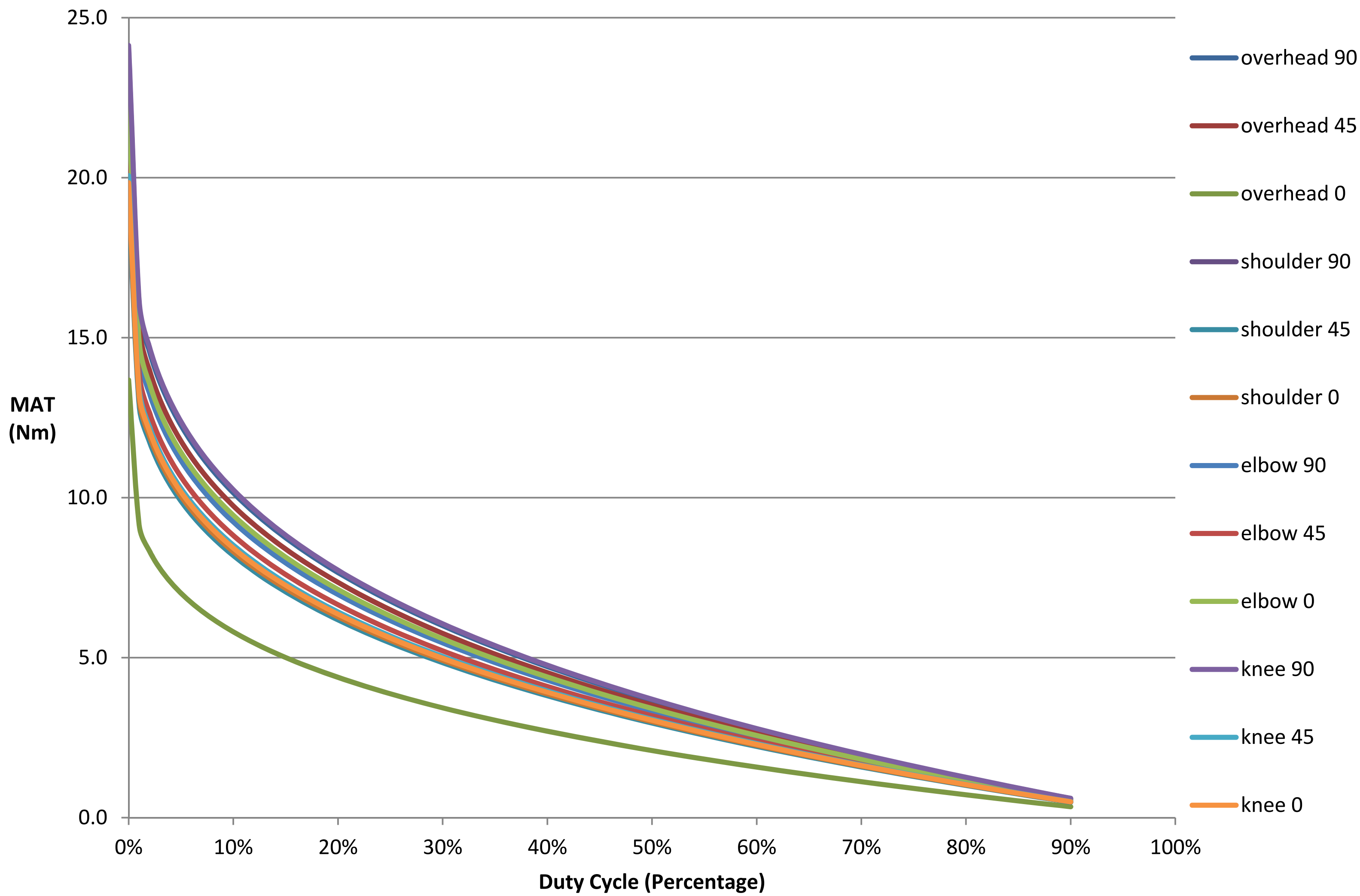


Figure 53: Recommended maximum acceptable torques (MAT) for handwheel-valve systems as a function of duty cycle and handwheel height and angle.

per day will be about 16 Nm, which is a torque demand that is within the capabilities of most of the population. If a higher DC value is considered, the estimated MAT will further decrease.

The DC value will depend on the total average time per day that is spent by one operator turning handwheels, which varies between industries. For instance, fire-fighters typically require about 2 minutes of continuous handwheel actuation to fully open or close a valve (Meyer et al., 2000). Jackson et al. (1992) mentioned that opening or closing valves in a chemical plant can involve continuous handwheel actuation as long as 15 minutes. The gate-way valve that was used in this research required up to two minutes to be fully opened by one of the participants. Also, the number of valves that need to be shut or open will vary between industries. The advantage of equation 5 is that it enables any plant to estimate its own MAT after measuring the average DC within its plant.

10.3 EMG Results

At each height-angle combination, EMG activities from the right and left anterior deltoids, trapezii, latissimi dorsi, and erector spinae muscles were measured. The maximum EMG activities of each muscle from the trials were normalized to the maximum EMG activity of the corresponding muscle's RC. The following sections present the results of the maximum EMG activity of each muscle as a percentage of the muscle's maximum RC (%RC).

10.3.1 Right Anterior Deltoid

Figure 54 presents the average maximum EMG activities of the right anterior deltoid during the maximal torque exertions at the different handwheel heights and angles. When the handwheel angle was at 90^{o} (vertically-oriented), the EMG activity and the height level had a positive relationship. Higher height levels were associated with higher EMG activities at the right anterior deltoid; whereas at 0^{o}, height and EMG activity had an inverse relationship. As the height of the handwheel increased, the EMG activity of the right anterior deltoid decreased. Unlike the other angles, at 45^{o}, no clear trend was observed. In summary, the height level associated with the highest or lowest EMG activity depends on the angle being observed, and vice versa. This finding is supported by the ANOVA results (Table 69), which found the interaction effect between height and angle to be significant ($p < 0.0001$). In other words, height and angle main effects should not be analyzed separately, but rather, each specific height-angle combination needs to be considered in the analysis.

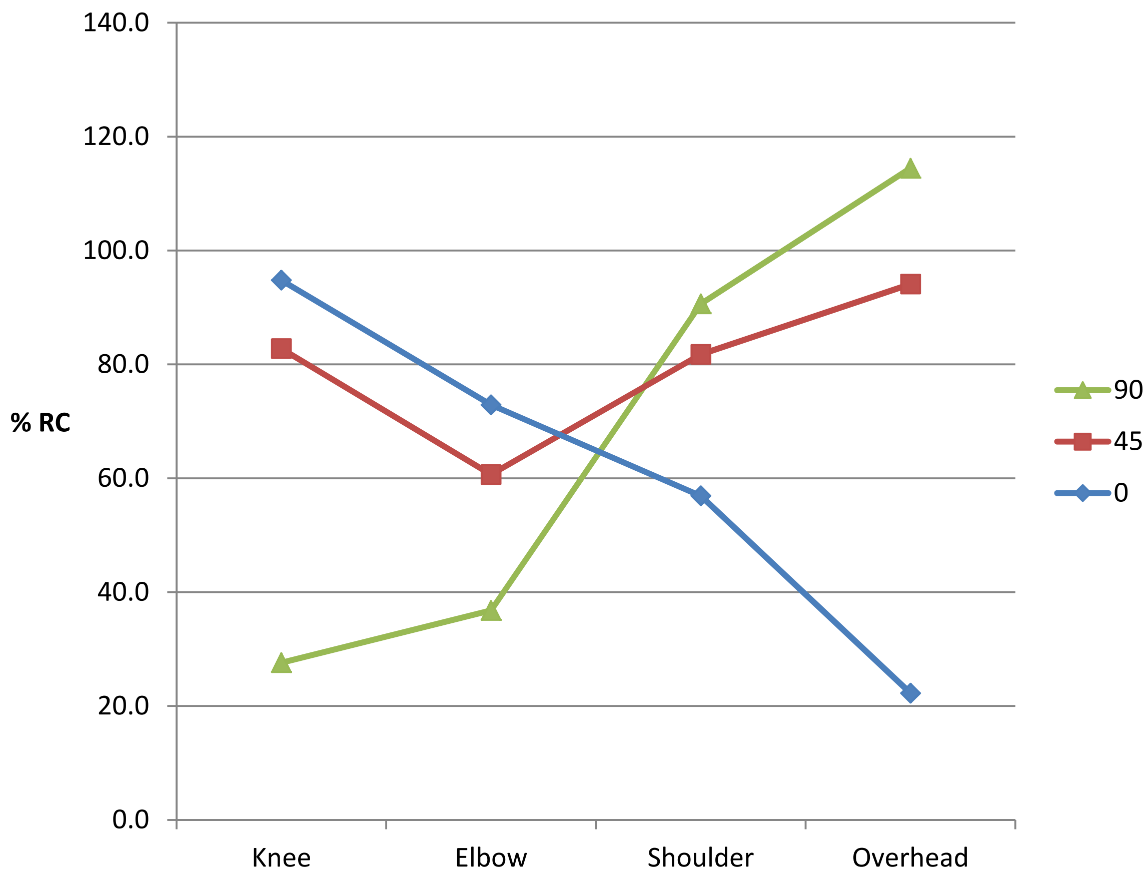


Figure 54: The average EMG activity of the right anterior deltoid muscle at each handwheel height-angle combination.

Table 69: ANOVA results for the average maximum EMG activity of the right anterior deltoid. A highlighted p-value indicates that the corresponding effect is significant.

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
H	3	42	4.22	0.0107
A	2	112	6.30	0.0025
H*A	6	112	24.01	<.0001

Table 70 summarizes the average maximum EMG activity of the right anterior deltoid and the standard deviation associated with each handwheel height-angle combination. Since the height-angle interaction effect was significant, a Tukey test was performed to determine the sources of the statistical significance in the interaction. Table 71 presents the Tukey results, grouping handwheel height-angle combinations into different letter groups. Handwheel positions in the same letter group indicate that no significant difference exists between them in the average maximum EMG activities of the right anterior deltoid; while handwheel positions in different letter groups indicate that significant differences exists between them in the average maximum EMG activities of the right anterior deltoid. The handwheel height-angle that required the most muscle activation of the right anterior deltoid was at overhead 90^o (114.4 %RC). According to the letter groupings, other handwheel positions that did not differ significantly from overhead 90^o were knee 0^o, overhead 45^o, shoulder 90^o, knee 45^o, and shoulder 45^o. At the other end of the spectrum, the handwheel position that required the least muscle activation was at overhead 0^o (22.3 %RC). Other handwheel positions that did not differ significantly from overhead 0^o included knee 90^o, elbow 90^o, and shoulder 0^o. Although at overhead 0^o the EMG activity of the right anterior deltoid was at its lowest, by only changing the angle to 90^o or 45^o, the EMG activity increased to or close to its peak.

Table 70: The average maximum EMG activity of the right anterior deltoid and the standard deviation associated with each handwheel height-angle combination.

Height	Angle	R. Ant Del (%RC)	
		Average	S.D.
Overhead	90	114.4	37.0
	45	94.1	54.7
	0	22.3	17.4
Shoulder	90	90.6	63.3
	45	81.8	48.6
	0	56.9	25.2
Elbow	90	36.8	22.0
	45	60.7	32.9
	0	72.9	35.8
Knee	90	27.6	17.8
	45	82.8	47.9
	0	94.8	39.4

Table 71: Tukey-Kramer output for the average maximum EMG activity of the right anterior deltoid at different handwheel heights (H) and angles (A).

H	**A**	**Estimate**	**Letter Group**				
Ov	90	114.4	A				
Kn	0	94.8	A	B			
Ov	45	94.1	A	B			
Sh	90	90.6	A	B	C		
Kn	45	82.8	A	B	C		
Sh	45	81.8	A	B	C		
El	0	72.9		B	C		
El	45	60.7		B	C	D	
Sh	0	56.9			C	D	E
El	90	36.8				D	E
Kn	90	27.6				D	E
Ov	0	22.3					E

10.3.2 Left Anterior Deltoid

Figure 55 presents a graph of the average maximum EMG activity of the left anterior deltoid at the different handwheel positions. Almost a similar trend can be seen for the 0^o and 45^o oriented handwheels. At knee and elbow level, the EMG activities were approximately equal, but beyond elbow level, the EMG activities increased. The 90° handwheel appears to have a different trend from the other two angles. From knee to shoulder level, the EMG gradually dropped, but then increased at overhead level.

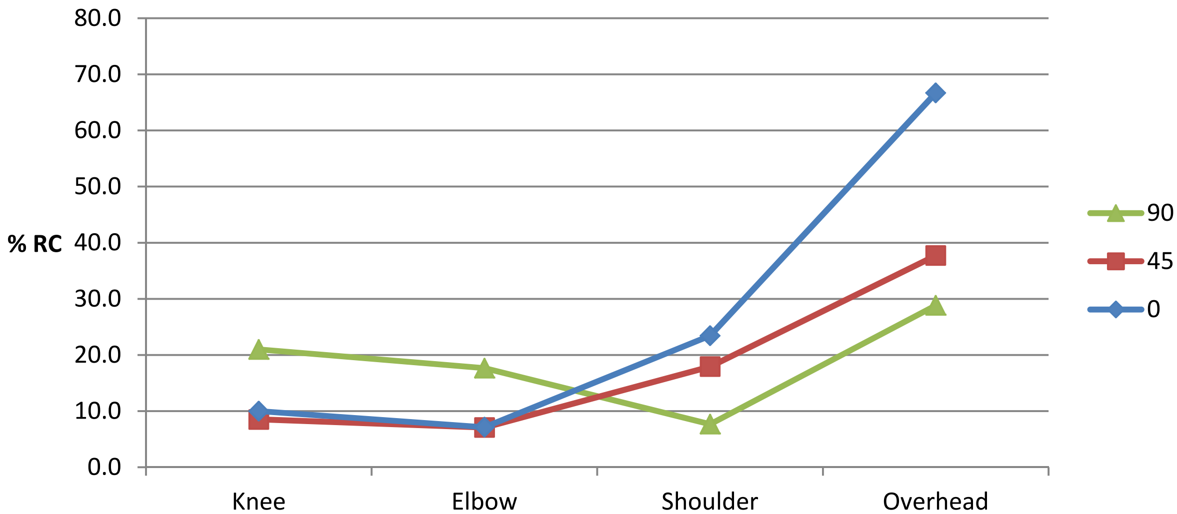


Figure 55: The average EMG activity of the left anterior deltoid muscle at each height-angle combination.

Since the trends differ across angles, inferences cannot be made from the main effects alone, but rather, they should be made from the interaction effect between height and angle. In other words, each height and angle combination must be considered in the analysis. This finding is supported by the ANOVA output, which found the interaction effect to be significant with a p-value less than 0.0001 (Table 72).

Table 72: ANOVA results for the average maximum EMG activity of the left anterior deltoid. A highlighted p-value indicates that the corresponding effect is significant.

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
H	3	42	25.74	<.0001
A	2	112	3.58	0.0310
H*A	6	112	5.41	<.0001

Table 73 summarizes the average maximum EMG activity of the left anterior deltoid and the standard deviation associated with each handwheel height-angle combination. Table 74 presents the Tukey results, grouping handwheel height-angle combinations that lack significant differences between each other in the EMG activities of the left anterior deltoid. The EMG activity of the left anterior deltoid was highest at overhead 0^o (66.7 %RC). The EMG activity at this handwheel position was significantly higher than the EMG activities at other handwheel heights and angles. On the other hand, the lowest EMG activity was found at elbow 45^o (7.1 %RC). According to the letter groupings, other handwheel heights and angles that did not differ significantly from this handwheel position include elbow 0^o, shoulder 90^o, knee 45^o, knee 0^o, elbow 90^o, shoulder 45^o, knee 90^o, shoulder 0^o, and overhead 90^o.

Table 73: The average maximum EMG activity of the left anterior deltoid and the standard deviation associated with each handwheel height-angle combination.

Height	Angle	L. Ant Del (%RC)	
		Average	S.D.
Overhead	90	28.8	25.0
	45	37.7	31.8
	0	66.7	39.6
Shoulder	90	7.7	3.4
	45	17.9	16.1
	0	23.4	10.5
Elbow	90	17.7	13.3
	45	7.1	4.0
	0	7.1	4.2
Knee	90	21.0	39.2
	45	8.5	6.2
	0	10.0	10.0

Table 74: Tukey-Kramer output for the average maximum EMG activity of the left anterior deltoid at different heights (H) and angles (A).

H	A	Estimate	Letter Group		
Ov	0	66.7	A		
Ov	45	37.7		B	
Ov	90	28.8		B	C
Sh	0	23.4		B	C
Kn	90	21.0		B	C
Sh	45	17.9		B	C
El	90	17.7		B	C
Kn	0	10.0			C
Kn	45	8.5			C
Sh	90	7.71			C
El	0	7.1			C
El	45	7.1			C

10.3.3 Right Trapezius

Figure 56 presents the average maximum EMG activities of the right trapezius muscle during the torque exertions at the different handwheel heights and angles. The EMG activity trends across the different heights for 0^o and 45^o are the same; however; at every height, the EMG activity was higher at 45^o than at 0^o. The EMG trend at 90^o, on the other hand, deviated from the trends found at 0^o and 45^o after shoulder level. While the EMG activity dropped from shoulder height to overhead height at both 0^o and 45^o, the EMG activity increased at the 90^o handwheel. According to the ANOVA test (Table 75), the interaction effect between height and angle was significant with a p-value of 0.0028. This significance indicates that inferences should be made from analyzing handwheel height-angle combinations.

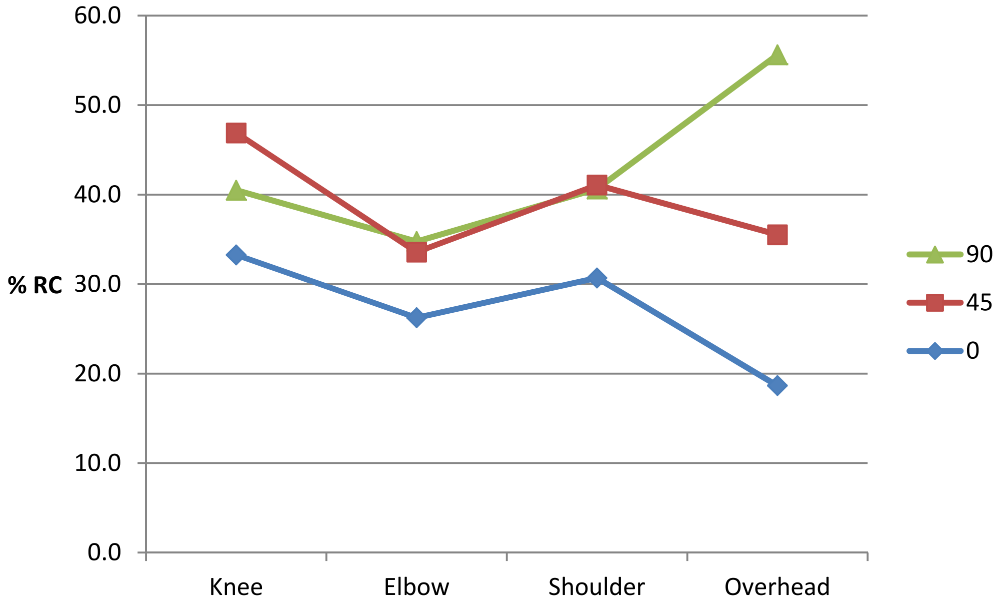


Figure 56: The average EMG activity of the right trapezius muscle at each height-angle combination.

Table 75: ANOVA results for the average maximum EMG activity of the right trapezius. A highlighted p-value indicates that the corresponding effect is significant.

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
H	3	154	2.37	0.0726
A	2	154	16.16	<.0001
H*A	6	154	3.51	0.0028

Table 76 summarizes the average maximum EMG activity of the right trapezius and the standard deviation associated with each handwheel height-angle combination. Table 77 presents the Tukey results, grouping handwheel height-angle combinations that lack significant differences between each other in the EMG activities of the right trapezius. The handwheel height and angle that was associated with the highest EMG activity at the right trapezius was at overhead 90^{o} (55.6 %RC). According to the letter groupings, other handwheel heights and angles that did not differ significantly from overhead 90^{o} were knee 45^{o}, shoulder 45^{o}, shoulder 90^{o}, and knee 90°. The handwheel height and angle that was associated with the least muscle activity was at overhead 0° (18.7 %RC). Other handwheel positions that did not differ significantly from overhead 0° included elbow 0°, shoulder 0°, knee 0°, elbow 45°, elbow 90°, and overhead 45°.

Table 76: The average maximum EMG activity of the right trapezius and the standard deviation associated with each handwheel height-angle combination.

Height	Angle	R. Trap (%RC)	
		Average	S.D.
Overhead	90	55.6	19.1
	45	35.5	19.0
	0	18.7	17.6
Shoulder	90	40.6	14.4
	45	41.1	23.9
	0	30.7	12.5
Elbow	90	34.8	19.3
	45	33.6	19.1
	0	26.2	13.3
Knee	90	40.5	19.5
	45	46.9	18.4
	0	33.3	25.7

Table 77: Tukey-Kramer output for the average maximum EMG activity of the right trapezius at different heights (H) and angles (A).

H	**A**	**Estimate**	**Letter Group**			
Ov	90	55.6	A			
Kn	45	46.9	A	B		
Sh	45	41.1	A	B	C	
Sh	90	40.6	A	B	C	
Kn	90	40.5	A	B	C	
Ov	45	35.5		B	C	D
El	90	34.8		B	C	D
El	45	33.6		B	C	D
Kn	0	33.3		B	C	D
Sh	0	30.7		B	C	D
El	0	26.2			C	D
Ov	0	18.7				D

10.3.4 Left Trapezius

Figure 57 presents the average maximum EMG activities of the left trapezius muscle at the various handwheel heights and angles. Almost a similar trend across heights can be seen for the 0^o and 45^o angles; however, the trend at 90^o differed, specifically at shoulder level. As the EMG activity increased from elbow level to shoulder level for 0^o and 45^o, the EMG activity remained almost the same for 90^o. According to the ANOVA test (Table 78), the interaction effect between the handwheel height and angle was significant with a p-value less than 0.0001. This finding suggests that inferences should not be made from the main effects alone, but rather, they should be made from the interaction effect between height and angle. In other words, each height and angle combination needs to be considered in the analysis.

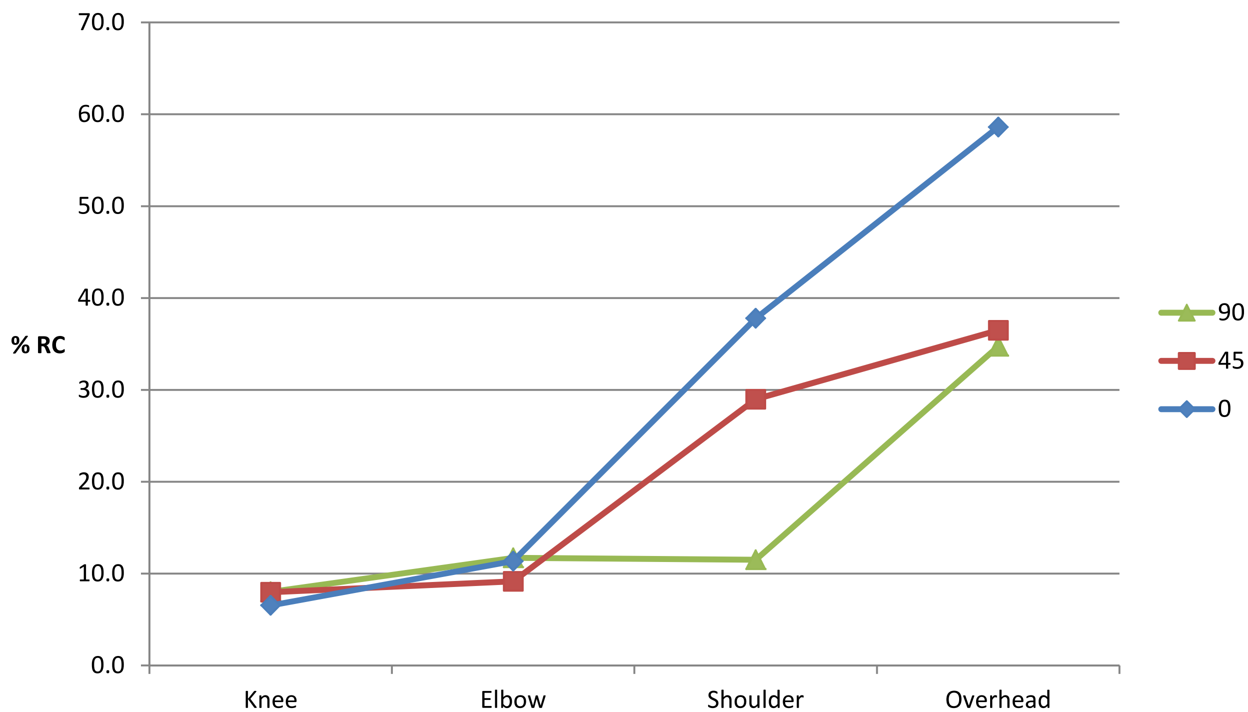


Figure 57: The average EMG activity of the left trapezius muscle at each height-angle combination.

Table 78: ANOVA results for the average maximum EMG activity of the left trapezius. A highlighted p-value indicates that the corresponding effect is significant.

Type 3 Tests of Fixed Effects				
Effect	Num DF	Den DF	F Value	Pr > F
H	3	42	44.70	<.0001
A	2	112	12.67	<.0001
H*A	6	112	5.83	<.0001

Table 79 summarizes the average maximum EMG activity of the left trapezius muscle and the standard deviation associated with each handwheel height-angle combination. Table 80 presents the Tukey results, grouping together handwheel height-angle combinations that lack significant differences between each other in the EMG activities of the left trapezius muscle. On the other hand, handwheel positions that are in different letter groups indicate that a significant difference in EMG activity of the left trapezius muscle exists between them. The handwheel positions are sorted in descending order of their EMG activities of the left trapezius. Overhead 0^o was associated with the highest EMG activity of the left trapezius muscle, requiring an EMG activity of 58.6 %RC. According to the letter groupings (Table 80), this handwheel position required significantly higher EMG activity than all other handwheel positions. On the other hand, knee 0^o was associated with the least muscle activity at the left trapezius muscle, requiring an EMG activity average of only 6.5 %RC. Other handwheel positions that did not differ significantly from knee 0^o included knee 45^o (8.0 %RC), knee 90^o (8.0 %RC), elbow 45^o (9.2 %RC), elbow 0^o (11.4 %RC), shoulder 90^o (11.5 %RC), and elbow 90^o (11.7 %RC).

Table 79: The average maximum EMG activity of the left trapezius and the standard deviation associated with each handwheel height-angle combination.

Height	Angle	L. Trap (%RC)	
		Average	S.D.
Overhead	90	34.7	27.0
	45	36.5	24.8
	0	58.6	24.4
Shoulder	90	11.5	7.9
	45	29.0	17.8
	0	37.8	19.0
Elbow	90	11.7	13.2
	45	9.2	8.3
	0	11.4	8.4
Knee	90	8.0	11.1
	45	8.0	4.7
	0	6.5	7.2

Table 80: Tukey-Kramer output of the average maximum EMG activity of the left trapezius at different heights (H) and angles (A).

H	**A**	**Estimate**	**Letter Group**			
Ov	0	58.6	A			
Sh	0	37.8		B		
Ov	45	36.5		B		
Ov	90	34.7		B		
Sh	45	29.0		B	C	
El	90	11.7			C	D
Sh	90	11.5				D
El	0	11.4			C	D
El	45	9.2				D
Kn	90	8.0				D
Kn	45	8.0				D
Kn	0	6.5				D

10.3.5 Right Latissimus Dorsi

Figure 58 shows the average maximum EMG activity of the right latissimus dorsi at the various handwheel heights and angles. Table 81 presents these averages and their associated standard deviations. Unlike the already discussed muscles, no similar trend was noticed between any of the angles; yet the ANOVA test did not find the interaction effect between height and angle to be significant (Table 82). The p-value of the interaction effect was 0.0614, which was not too far from the significance level of 0.05. A possible reason for the lack of significance could be because the range of the EMG activity was not large enough to be considered significant. All the averages for the different handwheel heights and angles fell within the range of 16.5 %RC and 38.2 %RC. This result indicates that the height and angle effects are independent of each other and can be interpreted separately.

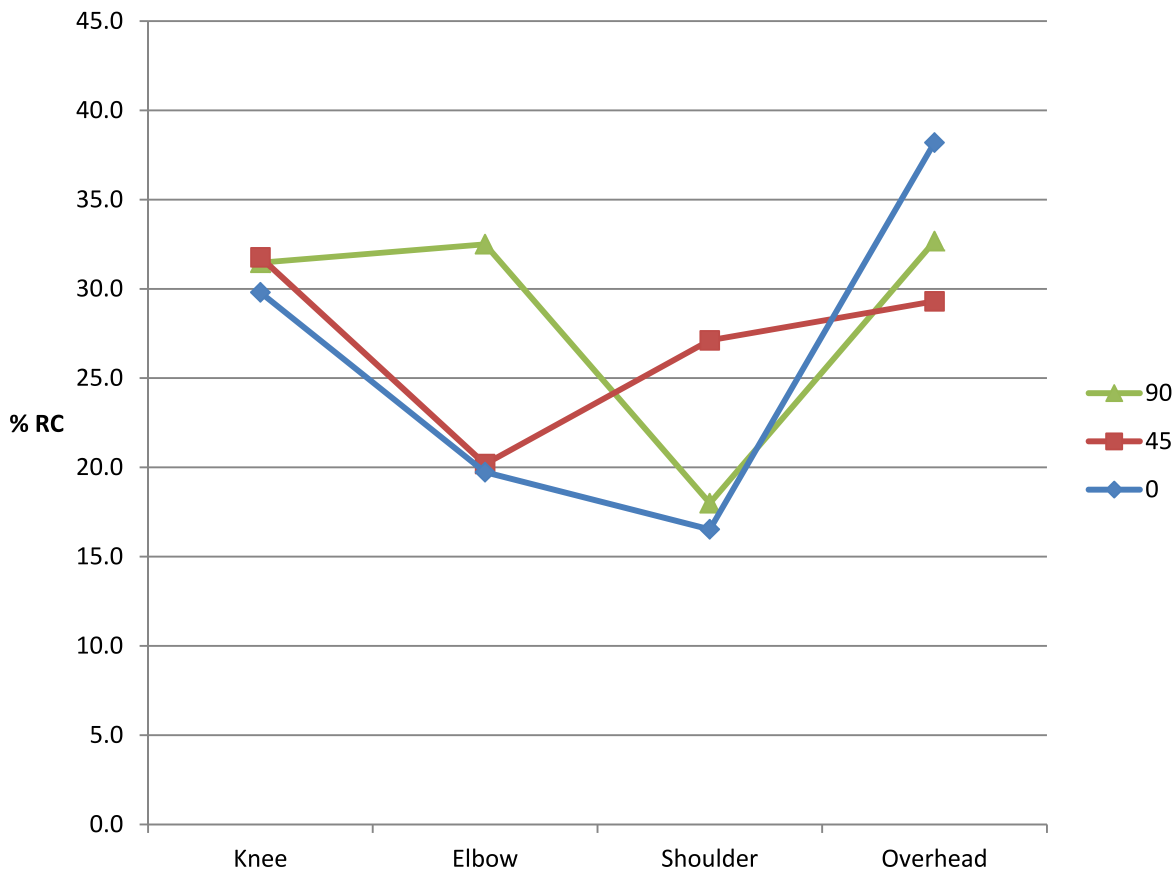


Figure 58: The average EMG activity of the right latissimus dorsi muscle at each height-angle combination.

Table 81: The average maximum EMG activity of the right latissimus dorsi and the standard deviation associated with each handwheel height-angle combination.

Height	Angle	R. Lat (%RC)	
		Average	S.D.
Overhead	90	32.7	18.8
	45	29.3	22.6
	0	38.2	22.8
Shoulder	90	18.0	9.7
	45	27.1	34.5
	0	16.5	11.6
Elbow	90	32.5	20.1
	45	20.2	8.5
	0	19.7	10.3
Knee	90	31.5	16.3
	45	31.8	21.0
	0	29.8	20.1

Table 82: ANOVA results for the average maximum EMG activity of the right latissimus dorsi. A highlighted p-value indicates that the corresponding effect is significant.

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
H	3	42	3.51	0.0233
A	2	112	0.43	0.6546
H*A	6	112	2.08	0.0614

Figure 59 graphs the average maximum EMG activities of the right latissimus dorsi muscle at the different handwheel heights averaged over all angles. Table 83 presents these averages and their associated standard deviations. The EMG trend across heights in ascending order was as follows: shoulder (20.5 %RC), elbow (24.1 %RC), knee (31.0 %RC), and overhead (33.4 %RC). The ANOVA test found the height effect to be significant with a p-value of 0.0233 (Table 82), indicating that at least one height level differed significantly from the other heights in EMG activity. According to the Tukey test (Table 84), the only significant difference in EMG was found between shoulder height and overhead height. The difference in EMG activity between these two heights was 12.9 %RC. No significant differences existed between any other pair-wise comparisons.

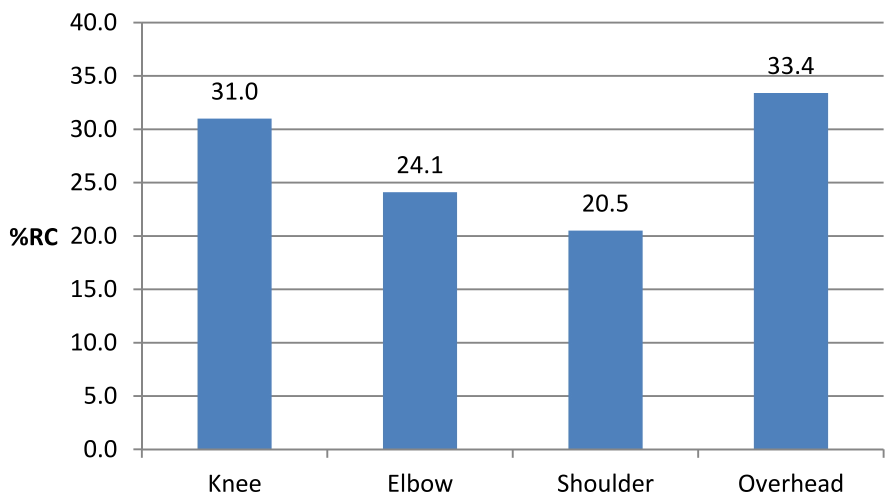


Figure 59: The maximum average EMG activity of the right latissimus dorsi muscle at the different heights.

Table 83: The overall average maximum EMG activity of the right latissimus dorsi and the standard deviation associated with each handwheel height.

Height	R. Lat (%RC)	
	Average	S.D.
Overhead	33.4	21.5
Shoulder	20.5	21.7
Elbow	24.1	13.9
Knee	31.0	19.3

Table 84: Tukey-Kramer output of the height main effect for the average maximum EMG activity of the right latissimus dorsi.

H	Estimate	Letter Group	
Ov	33.4	A	
Kn	31.0	A	B
El	24.1	A	B
Sh	20.5		B

Unlike the height main effect, the angle main effect was not significant with a p-value of 0.6546 (Table 82), indicating that the EMG activity of the right latissimus dorsi between angles did not differ. Figure 60 illustrates the average maximum EMG activities of the different angles averaged over all heights. Table 85 presents these averages and their associated standard deviations. All the angles were associated with approximately equal EMG activities at the right latissimus dorsi, ranging between 26.1 %RC and 28.7 %RC. In other words, the handwheel angle did not have much effect on the EMG behavior of the right latissimus dorsi muscle.

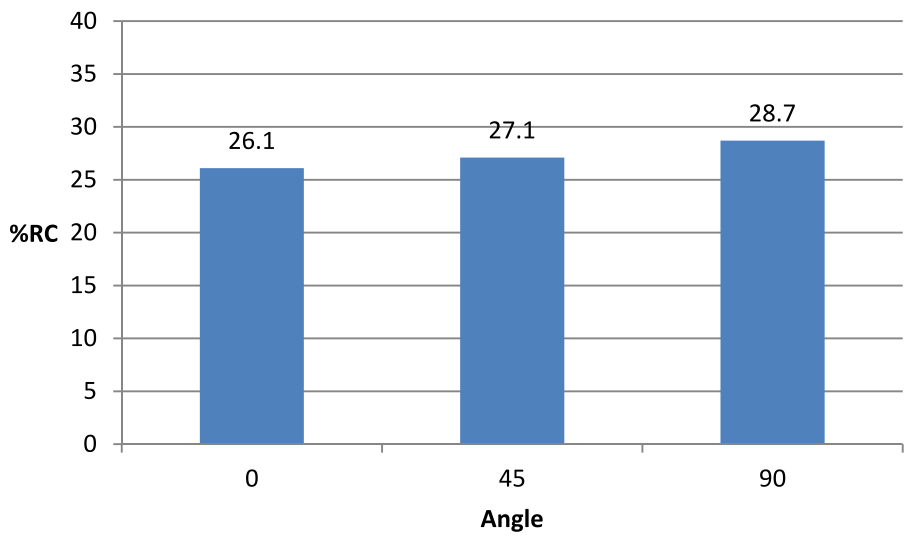


Figure 60: The maximum average EMG activity of the right latissimus dorsi muscle associated with the different handwheel angles.

Table 85: The overall average maximum EMG activity of the right latissimus dorsi and the standard deviation associated with each handwheel angle.

Angle	R. Lat (%RC)	
	Average	S.D.
90	28.7	16.7
45	27.1	23.5
0	26.1	17.1

10.3.6 Left Latissimus Dorsi

Figure 61 presents the maximum average EMG activities of the left latissimus dorsi during the torque exertions at the various handwheel heights and angles. The EMG trend across the different heights for each handwheel angle differed from each other, suggesting that the interaction effect between height and angle is significant. According to the ANOVA test (Table 86), the interaction effect between the handwheel height and angle was significant with a p-value less than 0.0001. This finding suggests that inferences should not be made from the main effects alone, but rather, they should be made from the interaction effect between height and angle. In other words, each height and angle combination needs to be considered in the analysis of the EMG activity of the left latissimus dorsi.

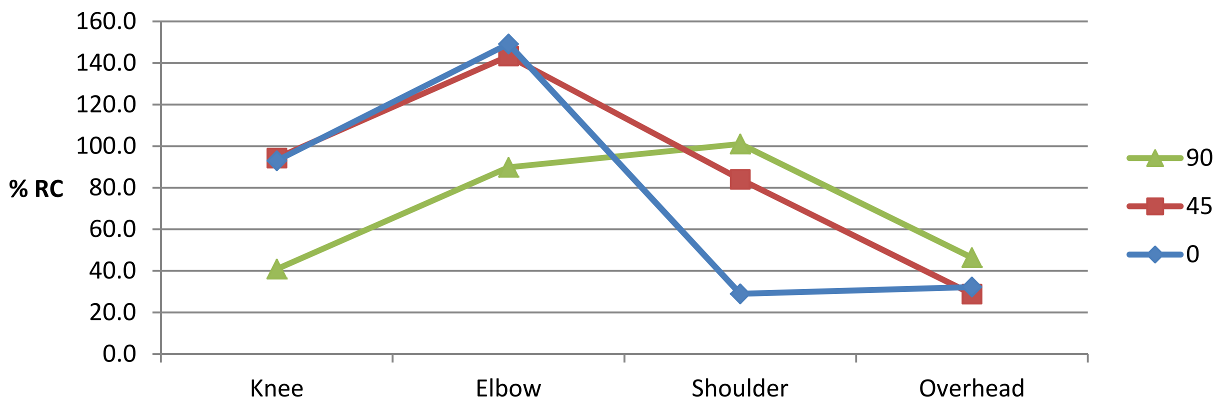


Figure 61: The average maximum EMG activity of the left latissimus dorsi muscle at each height-angle combination.

Table 86: ANOVA results for the average maximum EMG activity of the left latissimus dorsi. A highlighted p-value indicates that the corresponding effect is significant.

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
H	3	42	20.42	<.0001
A	2	112	5.37	0.0060
H*A	6	112	16.78	<.0001

Table 87 summarizes the average maximum EMG activity of the left latissimus dorsi and the standard deviation associated with each handwheel height-angle combination. Table 88 presents the Tukey results, grouping together handwheel height-angle combinations that lack significant differences between each other in the EMG activities of the left latissimus dorsi. Elbow 0^o was associated with the highest EMG activity from left latissimus muscle, which was 149.1 %RC. This value even exceeded the EMG of the muscle's maximum RC by 49.1 %RC. According to the letter groupings, other handwheel positions that did not differ significantly from elbow 0^o were elbow 45^o and shoulder 90^o. The EMG levels at both of these handwheel positions also exceeded the muscle's maximum EMG during its RCs. At the other end of the spectrum, the handwheel position that was associated with the least EMG activity of the left latissimus dorsi was at overhead 45^o (28.9 %RC). Handwheel positions that did not differ significantly from overhead 45^o in EMG activity included shoulder 0^o, overhead 0^o, knee 90^o, and overhead 90^o.

Table 87: The average maximum EMG activity of the left latissimus dorsi and the standard deviation associated with each handwheel height-angle combination.

Height	Angle	L. Lat (%RC)	
		Average	S.D.
Overhead	90	46.4	24.5
	45	28.9	19.1
	0	32.2	20.2
Shoulder	90	101.0	61.2
	45	84.0	60.4
	0	28.9	18.3
Elbow	90	89.8	39.9
	45	143.3	52.5
	0	149.1	80.6
Knee	90	40.9	41.3
	45	94.2	64.0
	0	93.0	55.5

Table 88: Tukey-Kramer output for the average maximum EMG activity of the left latissimus dorsi at different heights (H) and angles (A).

H	A	Estimate	Letter Group					
El	0	149.1	A					
El	45	143.3	A	B				
Sh	90	101.1	A	B	C			
Kn	45	94.2		B	C	D		
Kn	0	93.0			C	D		
El	90	89.8			C	D	E	
Sh	45	84.0			C	D	E	
Ov	90	46.4				D	E	F
Kn	90	40.9					E	F
Ov	0	32.2						F
Sh	0	28.9						F
Ov	45	28.9						F

10.3.7 Right Erector Spinae

Figure 62 graphs the average maximum EMG activities of the right erector spinae muscle at the various handwheel heights and angles. The EMG trend across the different heights at 45^o and 90^o were similar, while the trend at 90^o differed. At 45^o and 90^o, the EMG activity and height level had an inverse relationship. The EMG levels at these two angles were lowest at overhead level and highest at knee level. On the other hand, at 0^o, the EMG activity did not have a clear trend across the different height levels. The EMG at 0^o was highest at elbow level and lowest at shoulder level.

The difference in EMG trends among the different angles suggests that the interaction effect between height and angle to be significant, which was the case. The ANOVA test yielded a significant interaction effect with a p-value of 0.0288 (Table 89). This finding suggests that inferences should not be made from the main effects alone, but rather, they should be made from the interaction effect between height and angle. In other words, each height and angle combination needs to be considered in the analysis of the EMG activity of the right erector spinae.

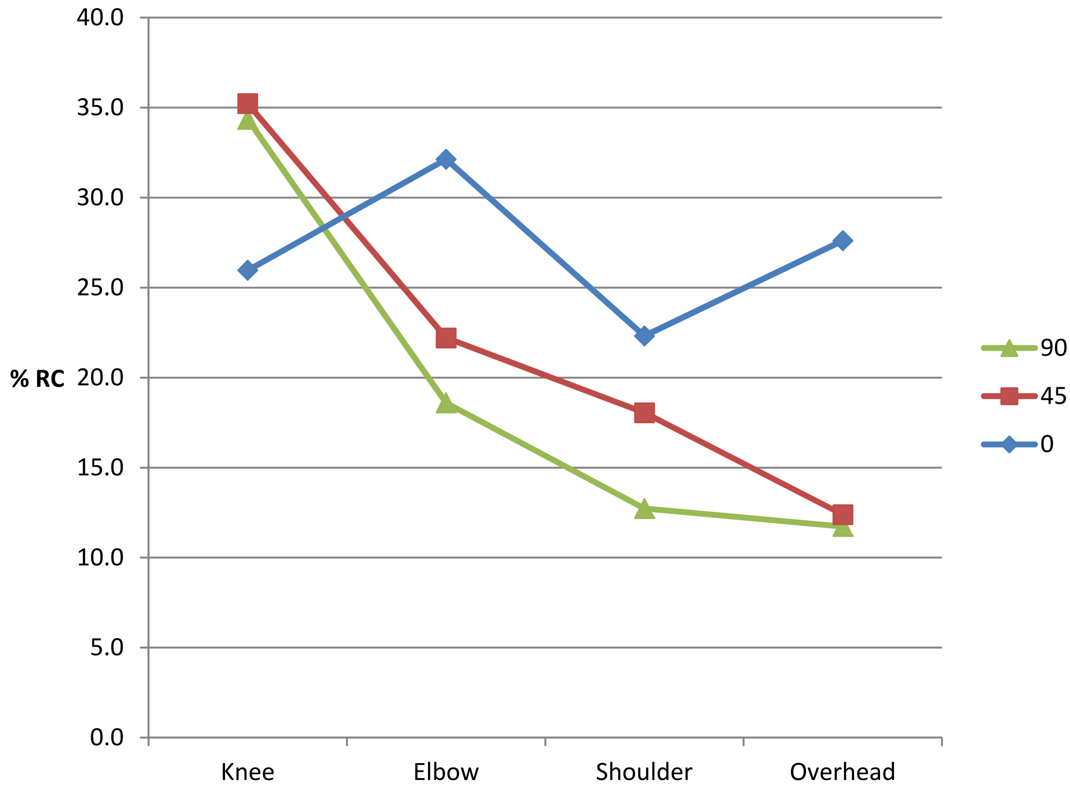


Figure 62: The average EMG activity of the right erector spinae muscle at each height-angle combination.

Table 89: ANOVA results for the average maximum EMG activity of the right erector spinae. A highlighted p-value indicates that the corresponding effect is significant.

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
H	3	42	5.71	0.0023
A	2	112	3.76	0.0264
H*A	6	112	2.45	0.0288

Table 90 summarizes the average maximum EMG activity of the right erector spinae and the standard deviation associated with each handwheel height-angle combination. Table 91 presents the Tukey results, grouping handwheel height-angle combinations that lack significant differences between each other in the EMG activities of the right erector spinae. The EMG activity was highest at knee 45^o, where it was 35.2 %RC. Many other handwheel positions did not differ significantly from the EMG at knee 45^o, including knee 90^o, elbow 0^o, overhead 0^o, knee 0^o, shoulder 0^o, elbow 45^o, elbow 90^o, and shoulder 45^o. At the other end of the spectrum, the handwheel position that was associated with the least EMG activity was at overhead 90^o, requiring only 11.7 %RC. Many handwheel positions did not differ significantly also from overhead 90^o, including overhead 45^o, shoulder 90^o, shoulder 45^o, elbow 90^o, elbow 45^o, shoulder 0^o, knee 0^o, overhead 0^o, and elbow 0^o.

Table 90: The average maximum EMG activity of the right erector spinae and the standard deviation associated with each handwheel height-angle combination.

Height	Angle	R. ES (%RC)	
		Average	S.D.
Overhead	90	11.7	4.9
	45	12.4	7.6
	0	27.6	20.8
Shoulder	90	12.7	7.4
	45	18.0	10.4
	0	22.3	15.6
Elbow	90	18.6	11.1
	45	22.2	17.9
	0	32.1	21.7
Knee	90	34.3	25.6
	45	35.2	37.3
	0	26.0	24.4

Table 91: Tukey-Kramer output for the average maximum EMG activity of the right erector spinae at different heights (H) and angles (A).

H	A	Estimate	Letter Group	
Kn	45	35.2	A	
Kn	90	34.3	A	
El	0	32.1	A	B
Ov	0	27.6	A	B
Kn	0	26.0	A	B
Sh	0	22.3	A	B
El	45	22.2	A	B
El	90	18.6	A	B
Sh	45	18.0	A	B
Sh	90	12.7		B
Ov	45	12.4		B
Ov	90	11.7		B

Unlike the other muscles, the variability of the EMG data for the right erector spinae muscle was not so large across the different handwheel positions. Therefore, not many pairwise comparisons between different handwheel positions were found as significant. According to the letter groupings, the EMG activity at knee 45^o and knee 90^o were significantly different from the EMG at shoulder 90^o, overhead 45^o, and overhead 90^o. These pairwise comparisons were the only ones found as significant.

10.3.8 Left Erector Spinae

Figure 63 illustrates in a graph the average maximum EMG activity of the left erector spinae associated with the different handwheel heights and angles. Table 92 presents these averages and their associated standard deviations. The EMG trends for each of the angles were almost the same across the different heights. The only exception was the 45^o handwheel between knee and elbow height, where it differed from the EMG trends of 0^o and 90^o. As the EMG activity increased for the 0^o and 90^o angles, the EMG activity remained approximately the same for the 45^o angle. However, from elbow level to overhead level, all the angles followed a similar decreasing trend. Since the EMG trends between the angles were almost parallel, the ANOVA test did not detect a significant interaction effect between height and angle with a p-value of 0.2788 (Table 93). This result indicates that the height and angle effects are independent of each other and can be interpreted separately.

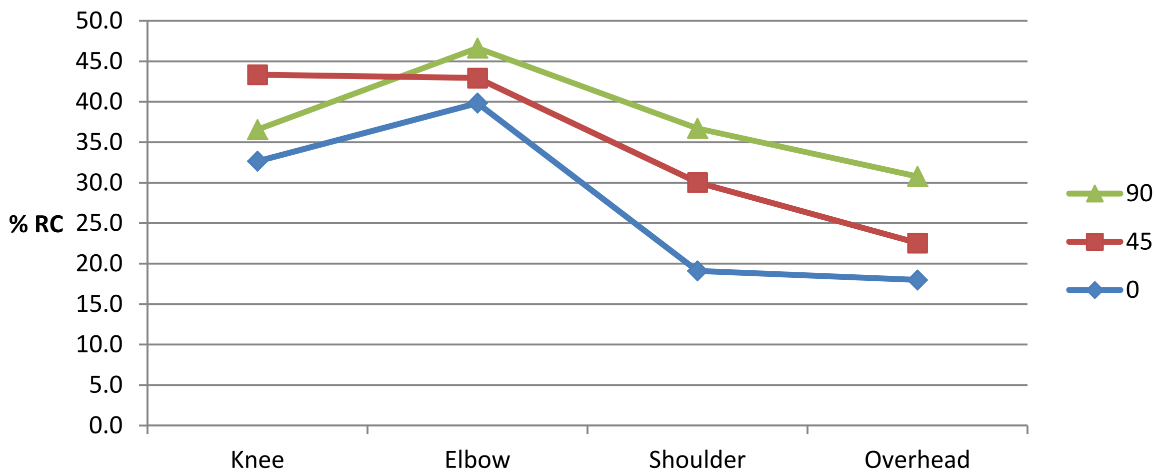


Figure 63: The average EMG activity of the left erector spinae muscle at each height-angle combination.

Table 92: The average maximum EMG activity of the left erector spinae and the standard deviation associated with each handwheel height-angle combination.

Height	Angle	L. ES (%RC)	
		Average	S.D.
Overhead	90	30.8	24.9
	45	22.5	15.2
	0	18.0	15.0
Shoulder	90	36.7	14.9
	45	30.0	13.8
	0	19.1	13.1
Elbow	90	46.6	17.6
	45	42.9	22.5
	0	39.8	18.0
Knee	90	36.6	20.2
	45	43.3	25.4
	0	32.6	10.3

Table 93: ANOVA results for the average maximum EMG activity of the left erector spinae. A highlighted p-value indicates that the corresponding effect is significant.

Type 3 Tests of Fixed Effects				
Effect	Num DF	Den DF	F Value	Pr > F
H	3	42	7.74	0.0003
A	2	112	8.52	0.0004
H*A	6	112	1.27	0.2788

Unlike the interaction effect, the height main effect was found to be significant with a p-value of 0.0003, indicating that at least one height differed significantly in EMG from the remaining heights. Figure 64 shows a bar graph of the average EMG activities of the left erector spinae across the different heights averaged over the three angles. Table 94 presents these averages and their associated standard deviations. The handwheel height that was associated with the least EMG activity was overhead (23.8 %RC), followed by shoulder (28.6 %RC), knee (37.5 %RC), and finally elbow (43.1 %RC).

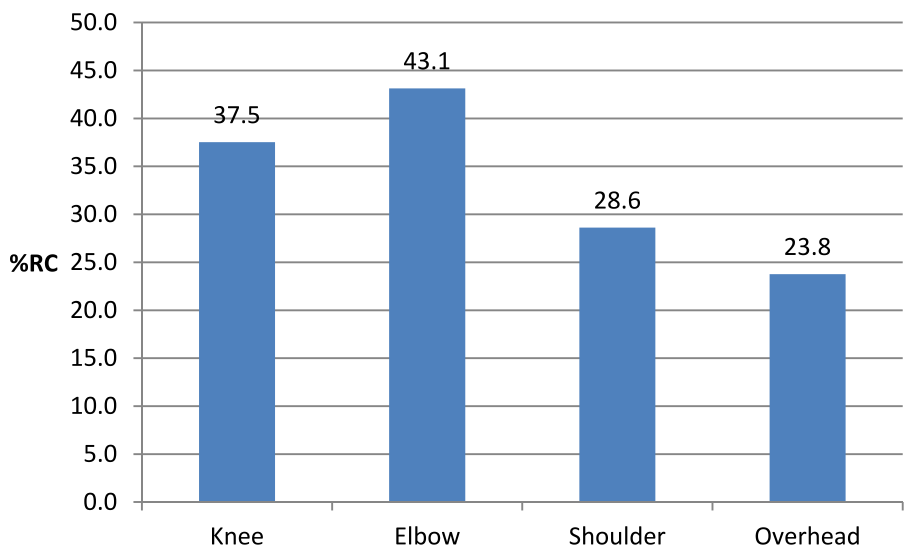


Figure 64: The average maximum EMG activity of the left erector spinae in terms of its RC across the different heights.

Table 94: The average maximum EMG activity of the left erector spinae and the standard deviation associated with each handwheel height.

Height	L. ES (%RC)	
	Average	S.D.
Overhead	23.8	19.0
Shoulder	28.6	14.0
Elbow	43.1	19.5
Knee	37.5	19.7

Table 95 summarizes the Tukey results for the height main effect. Although elbow height was associated with the highest EMG activity, knee height did not differ significantly in EMG activity from elbow height. The EMG difference between the two heights was only 5.6 %RC. Similarly, although overhead height was associated with the least EMG activity, it was not significantly lower than the EMG at shoulder level. The EMG difference between the two heights was only 4.8 %RC.

Table 95: Tukey-Kramer output for the average maximum EMG activity of the left erector spinae at the different heights (H).

H	**Estimate**	**Letter Group**		
El	43.1	A		
Kn	37.5	A	B	
Sh	28.6		B	C
Ov	23.8			C

The ANOVA test also yielded a significant angle main effect with a p-value of 0.0004, suggesting that at least one angle was significantly different from the other angles. Figure 65 shows the average maximum EMG activity of the left erector spinae at the various handwheel angles averaged over all four heights. Table 96 presents these averages and their associated standard deviations. As the handwheel angle increased, the EMG activity also increased. The EMG activity was 27.4 %RC at 0^o, 34.7 %RC at 45^o, and 37.7 %RC at 90^o. The 0^o angle was associated with significantly lower EMG activity than 45° and 90°, and the latter two angles were not significantly different from each other (Table 97). The EMG activity at 90° was only 3.0 %RC greater than the EMG activity at 45°.

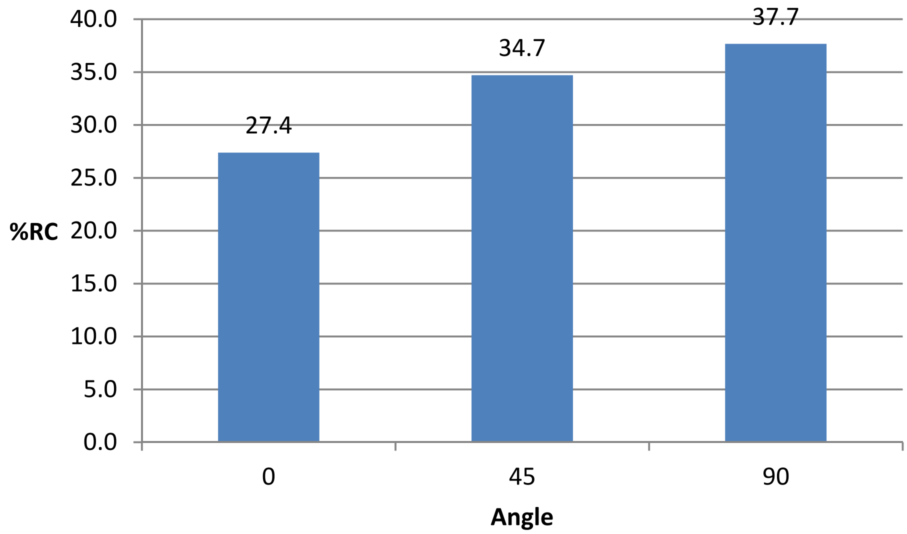


Figure 65: The average maximum EMG activity of the left erector spinae in terms of its RC across the different angles.

Table 96: The average maximum EMG activity of the left erector spinae and the standard deviation associated with each handwheel angle.

Angle	L. ES (%RC)	
	Average	S.D.
90	37.7	19.8
45	34.7	19.8
0	27.4	14.4

Table 97: Tukey-Kramer output for the average maximum EMG activity of the left erector spinae at the different angles (A).

A	**Estimate**	**Letter Group**	
90	37.7	A	
45	34.7	A	
0	27.4		B

10.4 Testing of Hypotheses

This research proposed three different hypotheses for all the dependent variables. Hypothesis 1 tested the height (H) main effect whether it had any significant difference(s) among the means of knee, elbow, shoulder, and overhead heights. Hypothesis 2 tested the angle (A) main effect to determine whether a significant difference existed among the means of handwheel angles 0^{o}, 45^{o}, and 90^{o}. Hypothesis 3 tested the interaction effect between height and angle (H*A) to determine whether a significant interaction effect existed these two factors. In addition to these hypotheses, four other hypotheses were proposed only for the maximum torque exertion because this dependent variable involved gender (G) as an additional factor. Table 98 presents all seven hypotheses and their associated p-values for each dependent variable. Hypothesis 4 tested the gender main effect to determine whether a significant difference existed between the males and females. Hypothesis 5 tested the interaction effect between gender and height (G*H) to determine whether a significant interaction effect existed between these two factors. Similarly, Hypothesis 6 tested an interaction effect but between gender and angle (G*A) to determine whether a significant interaction existed between these two factors. Finally, Hypothesis 7 involved all three factors testing the significance of the interaction between gender, height, and angle (G*H*A).

Beginning with the higher order interactions, the three-way interaction was not significant with a p-value of 0.1535, indicating that no significant interaction exists between gender, height, and angle. In other words, we failed to reject Hypothesis 7. On the other hand, Hypothesis 6 was significant (p-value = 0.0007) and hence, rejected. This result indicated that a significant interaction effect existed between gender and angle. Hypothesis 5 was not significant with a p-value of 0.3444, and hence, we failed to reject the null hypothesis. In other words, gender and height did not have a significant interaction effect on the maximum isometric torque exertions. Hypothesis 4 was significant with a p-value less than 0.0001. As a result, Hypothesis 4 was rejected, indicating that the mean torque productions between males and females were significantly different.

Table 98: The p-values associated with each dependent variable and hypothesis. Highlighted values represent significant p-values.

Hypotheses	(Effects)	Torque	R. Ant Del	L. Ant Del	R. Trap	L. Trap	R. Lat	L. Lat	R. ES	L. ES
Hypothesis 1	(H)	0.0002	0.0107	<.0001	0.0726	<.0001	0.0233	<.0001	0.0023	0.0003
Hypothesis 2	(A)	<.0001	0.0025	0.031	<.0001	<.0001	0.6546	0.006	0.0264	0.0004
Hypothesis 3	(H*A)	<.0001	<.0001	<.0001	0.0028	<.0001	0.0614	<.0001	0.0288	0.2788
Hypothesis 4	(G)	<.0001	---	---	---	---	---	---	---	---
Hypothesis 5	(G*H)	0.3444	---	---	---	---	---	---	---	---
Hypothesis 6	(G*A)	0.0007	---	---	---	---	---	---	---	---
Hypothesis 7	(G*H*A)	0.1535	---	---	---	---	---	---	---	---

For all the dependent variables, except the EMG activities of the right latissimus dorsi and left erector spinae, Hypothesis 3 was statistically significant. For the significant dependent variables, the null hypothesis was rejected, indicating that a significant interaction effect existed between height and angle. Hypothesis 2 was statistically significant for all the dependent variables but the EMG activity of the right latissimus dorsi. For the significant dependent variables, the null hypothesis was rejected, indicating that at least one angle mean was significantly different than the other angle mean(s). Also, Hypothesis 1 was statistically significant for all the dependent variables, except for one variable – the EMG activity of the right trapezius. For the significant dependent variables, the null hypothesis was rejected, indicating that at least one height mean was significantly different than the remaining height mean(s).

The raw data for the individual participants is provided in Appendix F, and the SAS programs for the ANOVA and Tukey-Kramer tests are provided in Appendix G.

CHAPTER 11: PROJECT-2 DISCUSSION

11.1 Comparison of Maximum Torque Data in the Current Study with Existing Guidelines

The MSSVFI has developed guidelines for the manual operation of valves in 1989. However, these guidelines have been poorly critiqued in the literature to have overestimated operators' capabilities (Attwood et al., 2002; Amell and Kumar, 2001). In 2009, the guidelines have been reviewed and published again (MSSVFI, 2009). Figure 2 is a graph reprinted from MSSVFI (2009) of operators momentary input force capability as a function of handwheel diameter. The MSSVFI defined momentary input force capability as "if an operator must apply a relatively high force to a manual actuator so as to cause a valve to break loose but may exert relatively lower forces to continue actuation of the valve, the initial high force is referred to as a momentary force." To determine whether the new guidelines are an adequate representation of operators' strengths, they were compared to the findings of this study.

In this research, the maximum isometric torque exertions were performed on a handwheel with a diameter of 37.4 cm (374 mm). According to Figure 2, the maximum force capability of operators at this diameter is approximately 1000 N. A 1000 N force acting on a 44 cm diameter handwheel is equivalent to a torque of 230 Nm. This value is far greater than all the average torques at the different handwheel heights and angles measured in this study. The highest average torque was found at overhead 45^{o}, which was 74.9 Nm. The difference between the highest average torque exertions of the operators in this study and the guideline's recommendation was 155.1 Nm. Even the highest torque exerted in this study, which was 108.1 Nm, was far below the guideline's estimate of operators' strengths.

There is no clear explanation as to why the operators' force capabilities in the guidelines are so large. The MSSVFI (2009) did not reference any studies on how it developed its estimates of operators' strengths. As Attwood et al. (2002) said, if their estimates were based on 'jerk' forces on handwheels, then they should not be used because it will promote actions that increase the risk of injury. It is recommended that the MSSVFI rim force recommendations be further investigated, considering the operators' strengths in this study and Attwood et al.'s (2002) study. Similar to this research, Attwood et al. (2002) had also used a large number of participants (66 process operators and managers) in measuring operators' maximum isometric exertions on handwheels of various heights and angles.

11.2 Comparison of Maximum Torque Data in the Current Study and Literature

One of the aims of this research was to conduct a comprehensive investigation of the effects of handwheel height and angle on operators' maximum torque production to address the mixed results in the literature. Wood et al.'s (1999/2000) study is the only research in the literature that investigated both male and female participants' torque production capabilities on a handwheel-valve, while others recruited only male participants. Therefore, the torque production data in Wood et al.'s (1999/2000) study were compared to the torques produced in the current study for both males and females. Table 99 summarizes the maximum torque measurements from Wood et al.'s (1999/2000) study and the current study for both genders. On the other hand, Hoff (2000), Attwood et al. (2002), and Wieszczyk et al. (2008) used only male participants. Therefore, their torque production data were compared to only the male participants' data of the current study. Table 99 also summarizes torque production results in these studies and the current study for only male participants.

At 0^{o} in the current study, the average maximum torque produced increased from knee to elbow height, but decreased as the handwheel height was raised further to shoulder and overhead heights. In other words, the average torque peaked at the elbow height handwheel position. On

Table 99: A summary of the maximum isometric torque data in the literature and the current research (Nm).

Handwheel Height	Male and female participants		Only male participants								
	90°		0°			45°		90°			
	Wood et al. (1999/ 2000)	Current Research	Attwood et al. (2002)	Hoff (2000)	Current Research	Attwood et al. (2002)	Current Research	Wieszczyk et al. (2008)	Attwood et al. (2002)	Hoff (2000)	Current Research
Overhead		73.2	111.8	36.5	71.0		98.1	153.3		72.4	97.2
Shoulder	47.59	72.4	143.3	70.1	84.9	130.0	94.1		152.9	74.5	96.0
Chest	46.76							138.9			
Elbow/Waist	44.06	61.1	154.8	68.0	91.1		88.0		140.5	72.2	82.8
Middle of Thigh	46.64										
Knee	43.52	65.6	163.3	69.2	86.9	142.4	79.4	146.6	136.5	72.3	87.9
Floor				64.8						77.6	

the other hand, Attwood et al.'s (2002) results showed a decline in the average maximum torque as height increased for a 0^o handwheel position. In Hoff's (2000) results, no clear trend was established for the torque production at 0^o. The small sample of participants (12 participants) in Hoff's (2000) research may have hindered the establishment of a trend.

At 45^o, the current study found height and the maximum torque to have a positive relationship; as the height level increased, so did the torque readings. Attwood et al. (2002) was the only other study that investigated 45^o handwheels for isometric torque exertions; however, their investigation was limited to only two height levels, which were knee and shoulder levels. Unlike this study, they found that as the handwheel height increased from knee to shoulder level the torque exertion decreased. A possible explanation as to why the results do not match could be due to different hand placements on the handwheel. The only information regarding hand placement in Attwood et al.'s (2000) research was that operators were required to grasp the wheel where the wheel and spoke joined. The current research had prevented participants from using the spoke, and asked them to use a hand placement similar to that found in Hoff (2000). A future research may investigate the effects of different hand placements on maximum torque exertions. The findings may explain the differences in the results and will determine the best hand placement for maximal torque production.

At 90^o, although no trend can be found, the height at which the maximum torque was produced was almost consistent across studies. In the current research, the highest torque for only males and both genders were found at overhead height (97.2 Nm and 73.2 Nm, respectively) and not far behind was shoulder height (96.0 and 72.4 Nm, respectively). Similarly, in the literature, either shoulder or overhead height was associated with the highest torque. Wood et al. (1999/2000) and Attwood (2002) found that participants were able to exert their highest torques at shoulder level. Overhead height at 90° was not even investigated in either of these studies. Hoff (2000) found floor level to be associated with the highest torque; however, her study was the only research to investigate floor level. Following floor level, shoulder height received the highest average torque. Another study by Wieszczyk (2008) found overhead height associated with the greatest torques. Participants were exerting higher torques at these levels (especially at overhead) possibly from utilizing body weight during torque exertions. After reviewing the literature and the results of the current study, it can be said that, at a 90° handwheel, overhead level is associated with the highest torques followed by shoulder level.

Similarly, at 45°, overhead height was associated with the highest torque (98.1 Nm) followed by shoulder level (94.1 Nm). In the contrary, Attwood et al. (2002) found the highest torques at knee level, which was the height at which participants exerted the lowest torque in the current research. Attwood et al. (2002) and the current research are the only two studies that investigated 45° angles. Both projects involved a large sample of participants, so sample size could have not been an issue. The issue, again, may be a result of the differences in hand placements between the two studies.

Although overhead height was associated with the highest torque at 45° and 90°, at 0° overhead height received the lowest torque exertions (71.0 Nm). At 0°, forces must be exerted in a horizontal plane, limiting the use of body weight in the torque exertions. On the other hand, at 45° and 90°, forces can be exerted in the downward direction, allowing participants to utilize their body weight in the exertions.

The height that was associated with the highest torques at 0° was elbow height. This finding confirms the results in Attwood et al.'s (2002) study, which also found elbow height to be associated with the greatest torques. Also, Hoff (2000) evaluated 0° handwheels. She found that shoulder height received the highest torque exertions. The differences in the results between Hoff's (2000) research and Attwood et al.'s (2002) and the current study could be due to the varying sample sizes. The low number of participants in Hoff's (2000) research may have deterred an accurate estimation of the torque means at the different handwheel heights and angles. On the other hand, Attwood et al. (2002) and the current research used a larger sample of participants. Therefore, it can be said with confidence that at 0^o handwheels elbow height enables the most torque production.

In the literature, there were only two studies that had investigated the effects of handwheel angle on maximum torque exertions, which were Hoff (2000) and Attwood et al. (2002). At knee height, the current research and Hoff (2000) found 90^o to be associated with the highest average torque, while Attwood et al. (2002) found the highest average torque at 0^o. At elbow height, the current research and Attwood et al. (2002) found the highest average torque at 0^o, while Hoff (2000) found 90^o to be associated with the highest average torque. At shoulder height, all the studies, including the current research, found that the 90^o handwheel allowed the highest torque production.

Regarding overhead height, only Hoff (2000) and the current research considered different handwheel angles in their analyses. Hoff (2000) considered only 0^o and 90^o, while the current research considered both those angles and 45^o. Both results yielded higher torque exertions at 90^o than at 0^o. The current research further found that 45^o handwheels were associated with even higher torque exertions, but the difference was not detected as statistically significant.

Overall, the current research discovered the highest average torque exertion to be at overhead 45^o for males alone and both genders (98.1 Nm and 74.9 Nm, respectively). Other angles that were not statistically different from this value included overhead 90^o, shoulder 90^o, and shoulder

45^o. These handwheel positions allowed greater torque production possibly because participants were able to utilize some of their body weight during the exertions, especially at overhead heights. Hoff (2000) found the greatest torque exertions at floor 90^o (77.6 Nm) – a handwheel position that was not investigated in the current research since it is a rare case in the field. Following floor 90^o, Hoff (2000) found shoulder 90^o with the highest torque results (74.5 Nm), which was among the handwheel positions that had the highest average torque in this research. Attwood et al. (2002) found the greatest torque exertions at knee 0^o, which does not match the results of this research. The differences could be a result of: the different hand placements used between this research and Attwood et al. (2002); the different populations sampled from (college students vs. process operators); whether participants were allowed to use body weight during overhead exertions or limited only to upper extremity use; or the different handwheel diameters used. Therefore, although this research found overhead 45^o with the highest torque, more research is still needed to verify this conclusion.

Although overhead 45^o allowed high torque productions, overhead 0^o was at the other extreme associated with the lowest average maximum torque exertion for males alone and both genders (71.0 Nm and 51.6 Nm, respectively). The average torque at this handwheel position was significantly lower than the torques at the remaining eleven handwheel positions. This finding is supported by the results of Hoff (2000) and Attwood et al. (2002), who also found that overhead 0^o associated with the lowest torques. There are two possible reasons for why this handwheel position limits torque production: 1) at this height and angle, participants are in an awkward posture, and typically, any deviation from the neutral posture reduces a person's force or torque production capabilities; and 2) unlike when the angle is slanted or vertically-oriented, using a horizontally-oriented handwheel makes it difficult to utilize body weight in the exertions since forces are only exerted in horizontal directions.

The majority of the research in the literature that sought to determine the optimum height and angle for a handwheel did so using only maximum torque production data. The approach in mind was to determine the height and angle at which operators can exert the highest torque as the optimum handwheel position. However, in the literature, all the studies found the handwheel positions associated with the highest torque to be at extremes deviating far from the neutral posture. For example, the highest average maximum torque was found to be at floor level in Hoff's (2000) study, at knee height in Attwood et al.'s (2002) research, at shoulder height in Wood et al.'s (1999/2000) research, and at overhead height in Wieszczyk et al.'s (2009) research and the current research. Such extreme positions, although they allow large torque production, may place greater loads on the shoulders and low back posing risks for MSD development. To address this matter, the current research measured the muscle loading of various trunk and shoulder muscles during the maximum torque exertions. The EMG results and the optimum handwheel height and angle with respect to EMG and torque data are discussed in the following sections.

11.3 The Selection of an Optimum Handwheel Height and Angle

In addition to the maximum torque measurements, this research has also measured the maximum EMG activities of the right and left anterior deltoids, trapezii, latissimi dorsi, and erector spinae muscles during the torque exertions at the different handwheel heights and angles. The aim was to find a handwheel position that would minimize muscle loading or at least distribute the load across different muscles, preventing heavy concentrated loads on any one muscle, and also permit substantial torque production from operators.

Table 100 summarizes the maximum torque exertions and the maximum EMG activities at the different heights and angles. The green values in the table represent the lowest EMG activity detected for the muscle or column; the yellow values represent EMG activities that were not considered as significantly different from the lowest EMG activity (green value) in the Tukey test; and the white cells are all other EMG activities, which were significantly different from the lowest EMG activity. Table 101 sorts the maximum handwheel heights and angles according to torque level from largest to smallest. The last column in both tables report the highest EMG activities associated with each handwheel height and angle.

Table 100 shows that most of the handwheel positions required that at least one muscle to sustain a substantial load. Some handwheel positions even required muscle activations greater than the maximum RC (> 100 %RC), including overhead 90^o (114.4 %RC of R-Del), shoulder 90^o (101.1 %RC of L-Lat), elbow 0^o (149.1 %RC of L-Lat), and elbow 45^o (143.3 %RC of L-Lat). From the remaining handwheel positions, several of them required muscle activation close to the maximum RC of at least one muscle, such as overhead 45^o (94.1 %RC of R-Del), shoulder 45^o (84.0 %RC of L-Lat and 81.8 %RC of R-Del), knee 0^o (94.8 %RC of R-Del and 93 %RC of L-Lat), elbow 90^o (89.8 %RC of L-Lat), and knee 45^o (94.2 %RC of L-Lat and 82.8 %RC of R-Del). These handwheel positions required that at least one muscle to work at EMG levels greater than 84 %RC placing a heavy concentrated load on one muscle, rather than distributing the load across different muscles. Hence, these handwheel positions were not considered in the selection of an optimum handwheel height or angle even if the torque associated with it was large.

Table 100: A summary of the maximum torque exertions at the different handwheel positions and their associated lowest EMG activities.

Height	Angle	R. Del	L. Del	R. Trap	L. Trap	R. Lat	L. Lat	R. ES	L. ES	Max Torque
Overhead	90	114.4	28.8	55.6	34.7	32.7	46.4	11.7	30.8	73.2
	45	94.1	37.7	35.5	36.5	29.3	28.9	12.4	22.5	74.9
	0	22.3	66.7	18.7	58.6	38.2	32.2	27.6	18.0	51.6
Shoulder	90	90.6	7.7	40.6	11.5	18.0	101.1	12.7	36.7	72.4
	45	81.8	17.9	41.1	29.0	27.1	84.0	18.0	30.0	70.7
	0	56.9	23.4	30.7	37.8	16.5	28.9	22.3	19.1	65.2
Elbow	90	36.8	17.7	34.8	11.7	32.5	89.8	18.6	46.6	61.1
	45	60.7	7.1	33.6	9.2	20.2	143.3	22.2	42.9	65.7
	0	72.9	7.1	26.2	11.4	19.7	149.1	32.1	39.8	68.9
Knee	90	27.6	21.0	40.5	8.0	31.5	40.9	34.3	36.6	65.9
	45	82.8	8.5	46.9	8.0	31.8	94.2	35.2	43.3	59.6
	0	94.8	10.0	33.3	6.5	29.8	93.0	26.0	32.6	67.6

Minimum EMG detected in muscle (column) — Not significantly different from minimum EMG — Significantly different from minimum EMG

Table 101: A summary of the average torque exertions at each handwheel height-angle combination in descending order.

H	A	Torque Nm	Letter Group	Highest EMG Activities
Ov	45	74.8855	A	94.1% R-Del
Ov	90	73.1633	AB	114.4% R-Del
Sh	90	72.3677	AB	101.1% L-Lat and 90.6% R-Del
Sh	45	70.7330	ABC	84.0% L-Lat and 81.8% R-Del
El	0	68.8977	BCD	149.1% L-Lat and 72.9% R-Del
Kn	0	67.6027	BCD	94.8% R-Del and 93% L-Lat
Kn	90	65.8783	CDE	40.9% L-Lat and 40.5% R-Trap
El	45	65.6567	CDE	143.3% L-Lat
Sh	0	65.2070	DE	56.9% R-Del
El	90	61.0888	EF	89.8% L-Lat
Kn	45	59.5780	F	94.2% L-Lat and 82.8% R-Del
Ov	0	51.6350	G	66.7% L-Del

The remaining handwheel positions that were left for the selection of an optimum handwheel position included knee 90^o, shoulder 0^o, and overhead 0^o. Table 102 reduces Table 100 to include only these three handwheel positions for better visibility and comparison. Overhead 0^o was associated with the least muscle activity in the right deltoid and trapezius and left erector spinae (green values). Also, the EMG at the left latissimus dorsi and right erector spinae were low to the point where the Tukey test did not detect a significant difference between them and their corresponding lowest values. On the other hand, the remaining three muscles – left deltoid and trapezius and right latissimus dorsi – were working at EMG levels greater than their corresponding lowest values. In summary, this handwheel position involved five muscles working at or close to their lowest EMG values and three muscles' working at levels significantly greater than the lowest EMG values.

Table 102: A summary of the EMG activities and maximum torques associated with the three handwheel positions, excluding the nine handwheel positions associated with high EMG activities.

Height	Angle	R. Del	L. Del	R. Trap	L. Trap	R. Lat	L. Lat	R. ES	L. ES	Max Torque
Overhead	0	22.3	66.7	18.7	58.6	38.2	32.2	27.6	18.0	51.6
Shoulder	0	56.9	23.4	30.7	37.8	16.5	28.9	22.3	19.1	65.2
Knee	90	27.6	21.0	40.5	8.0	31.5	40.9	34.3	36.6	65.9

Minimum EMG detected in muscle (column)
Not significantly different from minimum EMG
Significantly different from minimum EMG

One drawback for the overhead 0^o handwheel position is that it requires operators to work at higher percentages of their maximum strength than other positions. The reason so is that participants were not able to exert as much torque at this position as any other handwheel position. At this height and angle, participants exerted an average of 51.6 Nm, which was significantly less than all the average torques at other heights and angles.

Another drawback of this handwheel position is that it requires participants to work overhead, which may create greater risks of developing neck and shoulder pain. Overhead work is one of the most significant contributing factors to neck and shoulder pain (Holmström et al., 1992; Grieve and Dickerson, 2008). The results of this study do not differ with this conclusion as the left anterior deltoid and trapezius muscles were most active at overhead 0^o than any other height and angle. Also, several other studies have shown that arm elevation results in higher load on the shoulder and neck muscles. Nimbarte et al. (2009) evaluated the effects of isometric static lifting at different heights on the upper trapezius and sternocleidomastoid muscles. Their results show that as arm elevation increased from elbow to shoulder to overhead height, the EMG activity at both muscles increased. Similar results were found by Sood et al. (2002) in simulating an overhead task of automotive assembly work. They compared three overhead heights using subjective rating of perceived discomfort and EMG data of three shoulder muscles: anterior deltoid, middle deltoid, and trapezius. Their results show that higher EMG activity and perceived discomfort were associated with higher overhead heights. Also, Aghazadeh et al. (2012) found that arm elevation has a positive correlation of 0.39 to 0.75 with the trapezius muscle in a lifting task. Many other studies in the literature have concurred that higher arm elevation increases muscle activity and leads to a more rapid onset of fatigue (Garg et al., 2006; Ebaugh et al., 2006; Herberts and Kadefors, 1976; Järvholm et al., 1991; Jensen et al., 1999; Sporrong et al., 1996; Sporrong and Styf, 1999; Vasseljen and Westgaard, 1995). Therefore, overhead 0^{o} is not a considerable option for an optimum height and angle for handwheel.

At the shoulder 0^{o} handwheel position, seven out of the eight muscles were working at or close to their lowest EMG levels. The right latissimus dorsi was least active at this handwheel position at about 16.5 %RC. Six other muscles—including the right and left deltoids, right trapezius, left latissimus dorsi, and right and left erector spinae muscles—were working at low EMG levels that were not significantly different than their corresponding lowest EMGs. Only the left trapezius muscle was working at a level that was significantly greater than its lowest EMG (37.8 %RC). The average torque produced was fairly large at this handwheel position—approximately 65.2 Nm. This torque value was closer to the largest torque found in this study (74.9 Nm) than it was to the smallest torque (51.6 Nm). From the three handwheel positions in Table 102, shoulder 0^{o} received the second highest torque after knee 90^{o}; however the difference was negligible at only 0.7 Nm. The Tukey test did not find a significant difference between the average torques of the two handwheel positions. In summary, shoulder 0^{o} was associated with the least or close to least EMG activities across seven of the eight muscles and yet was associated with a fairly high torque.

An advantage of this handwheel position is that it requires relatively low EMG activities of the back muscles. Approximately 57% of the injuries in five petroleum companies were related to valve operations (Parks and Schulze, 1998). Hence, the need of reducing muscle loading on the back is a great concern in valve-operations. Of the three handwheel positions, shoulder 0^o required the least EMG activity of the right erector spinae—approximately 22.3 %RC. For the left erector spinae, it was also relatively low at 19.1 %RC. This EMG level was not significantly greater than the lowest EMG level of the left erector spinae, as the difference was only 1.1 %RC. Also, the EMG levels of the right and left latissimus dorsi were lowest at this handwheel position relative to the two other handwheel positions in Table 102. Even in comparison to all other handwheel heights and angles, the EMG of the right latissimus dorsi was lowest at this position.

At the knee 90^o handwheel position, none of the eight muscles were working at their lowest EMG levels; however, six muscles were working at levels not significantly different than the muscles' lowest EMG activities (yellow values). These muscles included right and left deltoid, left trapezius, right and left latissimus dorsi, and left erector spinae. On the other hand, the EMGs associated with the right trapezius and erector spinae muscles were significantly different than their respective lowest EMG. Of the three handwheel positions, this handwheel height and angle had the highest maximum torque readings with an average of 65.9 Nm; however, it was not significantly greater than the torque at shoulder 0^o. They only differed by 0.7 Nm. In summary, knee 90^o had six muscles working close to their minimum EMGs and was associated with a fairly high torque.

The downside to using a knee 90^o handwheel position is that it puts high loads on the low back relative to other handwheel positions. Of all twelve height-angle combinations, the EMG of the right erector spinae was second highest at this handwheel position, reaching an average maximum of 34.3 %RC. It was not significantly different than the highest EMG level, which was found at knee 45^o (35.2 %RC). The difference was less than 1 %RC between the two handwheel positions. As mentioned earlier, the prevalence of back injuries associated with valve operations makes the need of reducing the muscle loading on the low back even greater (Parks and Schulze, 1998). This handwheel position also loads the left latissimus dorsi the most of the three handwheel positions at about 40.9 %RC. Since this handwheel position places great loads on the back, it has also been omitted from the selection process along with overhead 0^o.

Therefore, the optimum height and angle of a handwheel appears to be at shoulder 0^o. At this height and angle, the reaction forces from the torque exertions were not concentrated at any one muscle, but rather the load was distributed on different muscles. Table 100 illustrates this distribution at shoulder 0^o, as its row has the most yellow and green EMG values. Seven of the eight muscles were working at or close to their lowest EMG activities. Of the three handwheel positions in Table 102, shoulder 0^o was associated with least muscle activity at all the back muscles with the exception of the right erector spinae, which only differed by 1.1 %RC from the lowest EMG activity. Also, at this handwheel position, participants were capable of producing fairly high torques reaching an average maximum of 65.2 Nm. Although other handwheel positions resulted in higher torques, they were eliminated early in the selection process because they were associated with concentrated loads on at least one muscle— as low as 84 %RC and as high as 149.1 %RC.

11.4 Handwheel Heights and Angles Associated with High Muscle Activities

Identifying handwheel positions associated with high muscle activities is just as much of a concern as to identify handwheel positions associated with low muscle activities. The high EMG activities inform about which handwheel positions require heavy muscle loadings and, in turn, should be avoided. In general, the higher the muscle loading, the higher is the risk of developing an MSD. Similar to Table 100, Table 103 summarizes the EMG results and maximum torque exertions at each height and angle, but uses different color-codes to highlight the most active muscles. A red-highlighted cell represents the highest EMG activity for the muscle (or column); an orange-highlighted cell indicates that its EMG level was not significantly different than the highest EMG or the red-cell in the same column; and a clear cell represents an EMG level that was significantly lower than the highest EMG activity.

Although the torque exertions were highest at overhead 45^o and 90^o, the shoulder and neck muscles were heavily loaded, receiving among the highest EMG activities relative to the other handwheel heights. For example, at overhead 90^o, the right deltoid EMG exceeded the EMG of its RC by over 14%. The right trapezius EMG activity was highest at this handwheel position, where it was approximately 55.6 %RC. At overhead 45^o, the right deltoid was also highly active, reaching an average maximum of 94.1 %RC. Overall, overhead 0^o appears to be the worst handwheel position, in that it was associated with the lowest torque exertions and yet high muscle loadings of the shoulder, neck, and back. The left anterior deltoid, trapezius, and right deltoid were most active at this handwheel position. Also, the right erector spinae EMG was relatively high at this handwheel position. The Tukey test did not find it to be significantly different than the highest EMG activity (at knee 45^o).

Table 103: A summary of the maximum torque exertions at the different handwheel positions and their associated highest EMG activities.

Height	Angle	R. Del	L. Del	R. Trap	L. Trap	R. Lat	L. Lat	R. ES	L. ES	Max Torque	Highest EMG Activities
Overhead	90	114.4	28.8	55.6	34.7	32.7	46.4	11.7	30.8	73.2	114.4% R-Del
	45	94.1	37.7	35.5	36.5	29.3	28.9	12.4	22.5	74.9	94.1% R-Del
	0	22.3	66.7	18.7	58.6	38.2	32.2	27.6	18.0	51.6	66.7% L-Del
Shoulder	90	90.6	7.7	40.6	11.5	18.0	101.1	12.7	36.7	72.4	101.1% L-Lat and 90.6% R-Del
	45	81.8	17.9	41.1	29.0	27.1	84.0	18.0	30.0	70.7	84.0% L-Lat and 81.8% R-Del
	0	56.9	23.4	30.7	37.8	16.5	28.9	22.3	19.1	65.2	56.9% R-Del
Elbow	90	36.8	17.7	34.8	11.7	32.5	89.8	18.6	46.6	61.1	89.8% L-Lat
	45	60.7	7.1	33.6	9.2	20.2	143.3	22.2	42.9	65.7	143.3% L-Lat
	0	72.9	7.1	26.2	11.4	19.7	149.1	32.1	39.8	68.9	149.1% L-Lat and 72.9% R-Del
Knee	90	27.6	21.0	40.5	8.0	31.5	40.9	34.3	36.6	65.9	40.9% L-Lat and 40.5% R-Trap
	45	82.8	8.5	46.9	8.0	31.8	94.2	35.2	43.3	59.6	94.2% L-Lat and 82.8% R-Del
	0	94.8	10.0	33.3	6.5	29.8	93.0	26.0	32.6	67.6	94.8% R-Del and 93.0% L-Lat

Maximum EMG detected in muscle (column) — Not significantly different from maximum EMG — Significantly different from maximum EMG

The results at shoulder 45^o and 90^o were quite similar to each other in the average torque exertions and EMG activities. The average torques at shoulder 45^o and 90^o were 70.7 Nm and 72.4 Nm, respectively, which according to the Tukey test were not significantly different from each other. At both handwheel positions, at least one side of the shoulders, neck, and back had high EMG activities that were not considered significantly different than the highest EMG activities. Specifically, the right deltoid, trapezius, and latissimus dorsi had EMG levels that were high relative to other handwheel positions. Also, the left latissimus dorsi was highly active at shoulder 90^o, even beyond its RC. Its average EMG activity at shoulder 90^o was 101.1 %RC. At shoulder 45^o, although the EMG level of the left latissimus dorsi was considered significantly lower than the highest EMG, it was still high at almost 84 %RC. Both shoulder 45^o and 90^o required the left erector spinae muscle to work at levels that were not significantly different from its highest EMG (at elbow 90^o). In summary, torque exertions at shoulder 45^o and 90^o required relatively heavy loadings of at least one side of the shoulders, neck, and back muscles.

In contrast, at shoulder 0^o, all the muscles, except for the right erector spinae, were working at EMG levels significantly lower than the highest EMG activities. The average EMG of the right erector spinae was 22.3 %RC, which was closer to the lowest EMG activity (11.7 %RC at overhead 90^o) than to the highest EMG activity (35.2 %RC at knee 45^o). Of all the handwheel heights and angles investigated, this handwheel position appears to have the best distribution of the loading across all muscles. This distribution is illustrated in Table 103, in that its row has the most number of clear cells than any other row, meaning that most of the muscles were working at levels significantly less than their highest EMG activities. In fact, seven of the eight muscles were working at EMG levels not significantly different from their lowest EMG activities. Overall, this handwheel position had the best loading distribution across the different muscles.

At elbow height, regardless of angle, the loadings on the shoulder and neck muscles were significantly lower than their highest EMGs. This is illustrated in Table 103, where all the cells for elbow height under the anterior deltoid and trapezii muscles were clear. However, the low loading of the shoulder and neck muscles is compensated by having the back muscles—both the latissimus dorsi and erector spinae muscles—work harder. About all the cells at elbow height for the latissimus dorsi and erector spinae muscles were either orange or red, meaning that these muscles had the highest or close to the highest EMG activities at this height. Even the clear cell for the left latissimus dorsi at elbow 90^{o} was highly active at approximately 89.8 %RC. Although this handwheel height was expected to be the best since its closest to the neutral posture, the results showed otherwise in that most of the loading was distributed on the back muscles.

These results are in agreement with the results of Wieszczyk et al.'s (2008) study. Their study is the only other research in the literature that compares different handwheel heights in terms of EMG measurements. Three different handwheel heights were considered in their study, including knee, chest, and overhead levels, at a fixed 90^{o} handwheel angle (vertically-oriented). They found that the right and left latissimus dorsi and erector spinae muscles were more active at chest height than at knee and overhead heights. This finding supports the results of the current research, which found elbow height to be associated with the greatest muscle loading on the latissimus dorsi and erector spinae muscles than knee, shoulder, and overhead heights.

Similar to elbow height, the torque exertions at knee height also appear to be strenuous for the trunk and back. As can be seen from Table 103, the EMG activities of the right latissimus dorsi, erector spinae, and left erector spinae at this height were not significantly different than the largest EMG activities found at other handwheel heights and angles. Even the significantly less EMG activities of the left latissimus dorsi were high at knee 0^{o} (93 %RC) and 45^{o} (94.2 %RC).

In addition to the heavy loading of the back, at knee height, at least one shoulder and/or neck muscle was highly active at EMG levels not significantly different from the highest EMG activities. For example, at knee 90^{o}, the right trapezius had an average EMG level of 40.5 %RC, which was not significantly different than the highest EMG (55.6 %RC at overhead 90^{o}). At knee 45^{o}, the EMG of the right trapezius was even higher (46.9 %RC), and also the right deltoid was found to be highly active at this handwheel position (82.8 %RC) relative to other handwheel positions. At knee 0^{o}, most of the muscle loading was concentrated on the right deltoid, resulting in an EMG activity of 94.8 %RC. In summary, knee height is not only associated with relatively heavy loadings on the back, but also on at least one shoulder and/or neck muscle.

11.5 Maximum Acceptable Torque

MATs for handwheel-valve systems were estimated in this study using the 5th percentile torque strength values of females. The estimated MATs for the different heights and angles investigated were quite low, ranging between 13.7 Nm and 24.1 Nm. Designing valve systems with such low torque demands may be difficult. Since this is the case, instead of using the 5th percentile values, MATs may be estimated using the 25th percentile strength values of females. Recommended force limits that accommodate 75% of females (or 25th percentile value), which in turn accommodates most males, have also been acceptable. For example, the committee of experts that developed the revised lifting equation in 1991 selected the psychophysical criterion to ensure that the job demands posed by manual lifting would not exceed the acceptable lifting capacity of about 75% of female operators, which is equivalent to the 25th percentile of females (Waters et al., 1993). This percentile value may not only be more practical in designing handwheel-valve systems but also more fitting because the majority of valve-operators are males. Table 104 presents the 25th percentile torque strength values of the female participants in this study.

Table 104: Maximum recommended torque limits calculated as the 25th percentile values of the female participants' maximum isometric exertions.

Height	Angle	Isometric Torque (Nm)
		25th percentile (females)
Overhead	90	36.8
	45	38.9
	0	25.2
Shoulder	90	37.9
	45	37.4
	0	34.7
Elbow	90	30.4
	45	33.6
	0	35.2
Knee	90	34.9
	45	30.2
	0	33.8

Using equation 5, MATs can be computed for tasks involving repetitive or continuous handwheel actuation. However, instead of using the 5th percentile value for T_{ij} in the equation, the 25th percentile value would be used. The 25th percentile values were at least 50% higher than the 5th percentile values, ranging between 25.2 Nm and 38.9 Nm. The highest 5th percentile value was smaller than the lowest 25th percentile value. Although that is the case, the 25th percentile values are still considered acceptable in establishing tolerance limit values (Waters et al., 1993). Ultimately, the selection of the appropriate torque limit will depend on the height and angle of the handwheel and the feasibility of designing for the 5th or 25th percentile.

CHAPTER 12: PROJECT-2 CONCLUSIONS

The aim of this research was to compare various handwheel heights and angles in terms of their associated maximal isometric torque exertions and EMG measurements of shoulder and trunk muscles; and then determine the optimum height and angle for a handwheel that maximizes torque production and minimizes muscle activity. The participants produced their greatest torques when the handwheel was set at overhead level in a 45^o angle. The average torque exertion for this handwheel position was 74.9 Nm. The downside to this handwheel position is that it was associated with a concentrated load on the right anterior deltoid. The average EMG activity of this muscle at overhead 45^o was 94.1 %RC, which did not differ significantly from the highest EMG activity (114.4 %RC, found at overhead 90^o). This high EMG activity indicates that the right shoulder is burdened with a substantial load when turning a handwheel at overhead 45^o.

Although the highest average torque was found at overhead 45^o, overhead 0^o was associated with lowest average torque, approximately 51.6 Nm. The average torque at overhead 0^o was significantly less than the average torques of the other handwheel heights and angles. This finding indicates that plant operators turning a handwheel at this position will be working at levels closer to their maximum capabilities than at other handwheel positions. Furthermore, three of the eight muscles investigated were most loaded at this handwheel position, including the left anterior deltoid (66.7 %RC), left trapezius (58.6 %RC), and right latissimus dorsi (38.2 %RC) muscles.

Based on the EMG results and the maximal torque exertions, the optimum height and angle of a handwheel appeared to be at shoulder 0^o. At this height and angle, the reaction forces from the torque exertions were not concentrated at any one muscle, but rather the load was distributed on different muscles. Seven of the eight muscles were working at or close to their lowest EMG activities. Only the left trapezius muscle was active at a level significantly greater than its lowest EMG activity (6.5 %RC, found at knee 0^o). Nevertheless, the EMG activity was still fairly low at an average of 37.8 %RC. Also, at this handwheel position, participants were capable of producing fairly large torques reaching an average maximum of 65.2 Nm. Although other handwheel positions resulted in higher torques, they were eliminated early in the selection process because they were associated with concentrated loads on at least one muscle – as low as 84 %RC and as high as 149.1 %RC.

Since elbow height is closest to the neutral posture, this research expected it to have the best loading distribution across the different muscles; however, that was not the case. Elbow height, regardless of angle, was associated with high loads on the back muscles, including both the latissimus dorsi and erector spinae muscles. The low loading of the shoulder and neck muscles was compensated by having the back muscles work harder. The latissimus dorsi and erector spinae muscles had the highest or close to the highest EMG activities at this height. Although this handwheel height was expected to be the optimum height, the results showed otherwise, in that most of the loading was distributed on the back muscles.

Using Potvin's (2012a) equation, this research created graphs of MATs as a function of DC (the percentage of time an individual is engaged in effort) for all the handwheel heights and angles. First, the 5^{th} percentile torque strength values of the female participants were computed at each height and angle. These values ranged between 13.7 Nm and 24.1 Nm, depending on the height and angle of the handwheel. They can be thought of as maximum recommended torque limits for the cracking torque or a single torque exertion on a handwheel. However, if an operator is expected to repetitively turn several handwheels per day, which is likely the case, then the torque demands should be even less than the acceptable strength for single exertions. Potvin's (2012a) equation was utilized to form a new equation for calculating MATs specifically for handwheel-valve systems at various heights and angles. The advantage of this equation is that it enables any plant to estimate its own MAT according to its average DC for valve operations.

CHAPTER 13: PROJECT-2 LIMITATIONS AND FUTURE RESEARCH

Several limitations were recognized before and during the performance of this research. One limitation is that participants were recruited from a student population instead of recruiting actual valve operators. Therefore, the results of this study may not be an accurate representation of the torque capabilities of valve operators. Valve operators are likely stronger than college students as can be noted in Wood et al.'s (1999/2000) and Wieszczyk et al.'s (2009) findings. Wood et al. (1999/2000) tested 24 male and female college students. The maximum torque exertions in their study ranged in the forty's. Wieszczyk et al. (2009), on the other hand, used 24 power plant mechanics and operators. They found that the maximum torque exertions ranged between 138.9 Nm and 153.3 Nm. The difference in torque exertions between these two studies is approximately 100 Nm.

Although the current research did not use plant operators, the torque data can still serve great benefit. The recommended maximum torque limits are likely lower using a student sample than it would have been from a sample of plant operators. The lower proposed torque will accommodate even more plant operators. Furthermore, this proposed torque can be treated as a recommended safe limit for novice plant operators, who have had no previous experience in valve operations.

Since participants were recruited only from the LSU student population, one may think that the results can represent only Louisianan valve-operators. However, the majority of the students recruited were either from other states in the U.S. or from entirely different countries, such as Bangladesh, Egypt, El Salvador, Honduras, India, Iran, Jordan, Palestine, and Venezuela. So the data collection was not only limited to participants from Louisiana. Nevertheless, caution should be used when attempting to generalize these results for other states or countries.

Furthermore, the torque results in this study are constrained to handwheels of size 37.4 cm in diameter. The interaction effects between handwheel diameter, height, and angle on torque production is still unknown. Future research in this area is still needed to determine the optimum design of a handwheel-valve system. Only Schulze et al. (1997) investigated the effects of different diameter handwheels on isometric torque exertions but at a fixed handwheel height (81.0 cm from the floor) and angle (horizontally-oriented). Four different diameters were considered in their study: 40.6 cm, 22.9 cm, 20.3 cm, and 17.8 cm. They found that the participants exerted significantly greater torques using the largest wheel. The medium 22.9 cm handwheel was associated with significantly larger forces than the two smaller wheels. These results seem valid since torque is proportional to the force exerted and the radius of the handwheel. Nevertheless, there should be a limit to the size of the handwheel; otherwise if the handwheel is too large, participants have to compromise effective upper extremity posture.

An additional factor that may have affected the torque production is the hand placement locations on the handwheel during the torque exertions. Participants were asked to adopt the same hand placement locations as in Hoff's (2000) study. This may explain why the range of the torque data in this study was most similar to Hoff's (2000) study. A future study may investigate the effects of various hand placement locations on a handwheel on isometric torque exertions. Such a study may explain the mixed results in the literature, and also, it may determine the best hand placement locations that will assist maximum torque production.

Follow-up research for this study may evaluate different handwheel heights and angles in continuous handwheel actuation. The analysis of the different handwheel positions may be based on the EMG activity of trunk, shoulder, and neck muscles; maximum heart rate; maximum oxygen consumption; Borg-ratings; and the time to fully open the valve. In the field, continuous effort of turning a handwheel to a fully closed or open position can take as long as 15 minutes (Jackson et al., 1992). Fifteen minutes or even five minutes of continuous handwheel actuation may be more physically and physiologically demanding than the initial cracking torque because continuous handwheel actuation requires continuous muscular effort at high torques for a period of time (Jackson et al., 1992). Despite the greater demands associated with continuous handwheel actuation, it has been much less researched in the literature than the initial cracking torque. Only three studies in the literature addressed continuous handwheel actuation, which were Jackson et al. (1992), Meyer et al. (2002), and Aghazadeh et al. (2012). Of the three studies, Meyer et al. (2002) was the only research that considered different handwheel positions; however, only three different handwheel configurations were examined in their study: (1) a horizontally-oriented handwheel at elbow height; (2) a vertically-oriented handwheel at elbow height; and (3) a horizontally-oriented handwheel at 70 cm from the floor. A more comprehensive research is necessary to determine the optimum height and angle for a handwheel.

Another future research may evaluate different handwheel heights and angles while using a valve-wrench. Since the torque demands in the field normally exceed operators' capabilities, the operators are bound to use a valve-wrench to open/close valves. For example, Jackson et al. (1992) measured the cracking torque of 217 valves in a chemical plant and found that 93% of the valves required torques over 400 Nm, which is much greater than the torques recorded in this study; the torque averages in this study ranged between 51.6 Nm and 74.9 Nm depending on the height and angle of the handwheel. The discrepancy between the torque demands and the capabilities of operators makes valve-wrenches a commonly used tool in valve operations.

Therefore, it should be included in the analysis of determining an optimum height and angle for handwheels.

In summary, the following research are recommended for future work:

- Compare different handwheel heights and angles among a large sample of experienced valve-operators (instead of college students) to identify the optimal height and angle of a handwheel and to determine operators' torque production capabilities.
- Determine the interaction effects of handwheel height, angle, and diameter on EMG activities and maximum isometric torque exertions.
- Investigate the effects of various hand placement locations on a handwheel on isometric torque exertions.
- Evaluate different handwheel heights and angles in continuous handwheel actuation using various measures (i.e. EMG activity; maximum heart rate; maximum oxygen consumption; Borg-ratings; discomfort ratings; the time to fully open the valve).

This project may be a useful source in the development of guidelines for valve systems, in that it proposes maximal acceptable torque limits for handwheel-valves. Also, this research determined an optimal handwheel height and angle for cracking torque exertions, considering not only isometric torque measurements but also EMG activities of shoulder and trunk muscles. Furthermore, this research is one of the most comprehensive studies in the literature investigating four handwheel heights, three angles, and their combinations.

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APPENDIX A: SAMPLE SIZE DETERMINATION

The sample size needed to estimate the mean torque production capabilities of the population was calculated using the method found in Machin et al. (1997). The calculations performed were based on preliminary data of ten male and ten female participants. The program used to estimate the population mean is provided in the following link:

- http://www.stattools.net/SSizmean_Pgm.php

The standard deviation of the maximum isometric torque exertions was 11.6 ft-lb for the male participants and 9.6 ft-lb for the female participants. To create a 95% confidence interval with a margin of error of ± 5 ft-lb, a sample size of 21 was needed for males and 15 for females. However, according to the literature, a sample size of 30 is enough to estimate a population mean (Hogg and Tanis, 2005). Since the literature sample size was greater than the calculated sample sizes for males and females, this study used 30 male and 30 female participants. A power analysis was also performed to determine whether a sample of 60 participants had sufficient power to detect differences in the means (discussed in the following section). According to Cohen (1988), the minimum suggested power for an ordinary study is 80%.

The following procedure was used for conducting the power analyses:

1. Constructed the fully specified summary ANOVA table for the fixed effects with their corresponding numerator (df_n) and denominator degrees of freedom (df_d).
2. Computed the non-centrality parameter for each fixed effect using the following equation
$$\lambda_\theta = n_\theta \delta^2/2$$
   Where:
   - λ_θ: is the non-centrality parameter for effect θ;
   - n_θ: is the number of observations per level of the effect θ;
   - δ: is the minimum difference between effects to be detected as significant in a root mean square error sense.

3. Inputted the values for df_n, df_d, and λ_θ in the following SAS code to find the power of each fixed effect:

```
data;
fcritical = finv (0.95, dfn, dfd, 0);
power = 1 – probf (fcritical, dfn, dfd, λθ);
run;
proc print; run;
```

Power Analysis for Project-1:

The table below is the fully specified summary ANOVA table for the fixed effects. The values for the numerator and denominator degrees of freedom (df) and the non-centrality parameter are listed for each fixed effect. Based on these values, project-1 has a power of at least 81%.

Fixed Effects	Num df	Den df	# of obs per level of the effect per participant	subject	n_θ	λ (δ = 1.25)	Power (δ = 1.25)
T	1	14	4	15	60	46.9	100.0%
M	3	84	2	15	30	23.4	98.6%
T*M	3	84	1	15	15	11.7	81.0%

Power Analysis for Project-2:

The table below presents the fully specified summary ANOVA table for project-2, including the numerator and denominator df and the non-centrality parameter. Based on these values, project-2 has a power of at least 92.1%.

Fixed Effects	Num df	Den df	# of obs per level of the effect per participant	subject	n_θ	λ (δ = 1.25)	Power (δ = 1.25)
G	1	58	36	60	1080	843.8	100.0%
H	3	174	9	60	540	421.9	100.0%
A	2	464	12	60	720	562.5	100.0%
R	2	1392	12	60	720	562.5	100.0%
G*H	3	174	9	60	270	210.9	100.0%
G*A	2	464	12	60	360	281.3	100.0%
G*R	2	1392	12	60	360	281.3	100.0%
H*A	6	464	3	60	180	140.6	100.0%
H*R	6	1392	3	60	180	140.6	100.0%
A*R	4	1392	4	60	240	187.5	100.0%
G*H*A	6	464	3	60	90	70.3	100.0%
G*H*R	6	1392	3	60	90	70.3	100.0%
G*A*R	4	1392	4	60	120	93.8	100.0%
H*A*R	12	1392	1	60	60	46.9	99.9%
G*H*A*R	12	1392	1	60	30	23.4	92.1%

APPENDIX B: PHYSICAL ACTIVITY READINESS QUESTIONNAIRE (PAR-Q)

For most people physical activity should not pose any problem or hazard. PAR-Q has been designed to identify the small number of adults for whom physical activity might be inappropriate or those who should have medical advice concerning the type of activity most suitable for them.

YES	NO	
☐	☐	1. Has your doctor ever said you have a heart trouble? should only do physical activity recommended by a doctor?
☐	☐	2. Do you frequently suffer from chest pain?
☐	☐	3. Do you often faint or have spells of severe dizziness?
☐	☐	4. Has your doctor ever said your blood pressure was too high?
☐	☐	5. Has your doctor ever told you that you have a bone or joint problem such as arthritis that has been aggravated by, or might be made worse with exercise.
☐	☐	6. Is there any good physical reason why you should not follow an activity program even if you want to?
☐	☐	7. Are you 65 and not accustomed to vigorous exercise?

If you answer "yes" to any question, vigorous exercise or exercise testing should be postponed. Medical clearance may be necessary.

I have read this questionnaire, I understand it does not provide medical assessment in lieu of a physical examination by a physician.

Participant's signature: __________________ Date: __________________

Investigator's signature: __________________ Date: __________________

Adopted from PAR-Q validation report, British Columbia department of Health, June 1975.

Reference: BQ Hafen, WWK Hoeger (1994), Wellness: Guidelines for a healthy lifestyle. Englewood, Colo.: Morton Pub. Co.

APPENDIX C: INFORMED CONSENT FORM

Study Title: The investigation of valve operators' torque production capabilities and optimal handwheel height, angle, and opening technique.

Performance site: Louisiana State University Department of Mechanical and Industrial Engineering: (1) Work Evaluation Laboratory, 3413 Patrick Taylor Hall; and (2) Human Factors Engineering Lab, 3412 Patrick Taylor Hall.

Investigators: Dr. Fereydoun Aghazadeh, (225) 578-5367, 3132-B Patrick Taylor Hall; Saif K. Al-Qaisi, IE Graduate Student, (225) 578-5377, 3412 Patrick Taylor Hall

Purpose of the Study: The purpose of this study is to evaluate various methods of opening manual gate valves (project 1) and also to evaluate heights and angles of handwheels (project 2) using electromyography of core muscles.

Participant Inclusion: primarily students, both male and female, from Louisiana State University (LSU), ages 18-60.

Exclusion Criteria: Individuals that have the following conditions:

- Cardiovascular diseases (including the use of a pacemaker or other electronic implant)
- Musculoskeletal disorders (Pain due to muscles, joints, tendons, ligaments, or nerves)
- History of chronic back, shoulder, or other musculoskeletal disorder
- Current pain that would affect performance of the tasks involved in the study
- Any answers of "yes" on the PAR-Q (to be given after this form is signed)

Number of Participants: 15 male participants for project 1; 15 male participants for project 2a; 30 male and 30 female participants for project 2b.

Study Procedures: You will first read this consent form and be given a verbal explanation of three projects (project 1, 2a, and 2b). If you agree to the terms of participation, place a check next to the project(s) that you will participate in and sign the end of this form. Then complete the PAR-Q (Physical Activity Readiness Questionnaire) questionnaire. At any time during the experiment, if more than normal task operating discomfort is encountered, please cease activity. All projects will begin with a warm-up session on a treadmill for five minutes at three miles per hour.

□ **Project 1 Study Procedures:** In this project, you will be required to open and close a valve-system a total of eight times. You will be connected to an electromyography (EMG) device which is an instrument that measures the activity of muscles. Eight adhesive electrodes will be attached on several trunk and shoulder muscles. There will be four methods to opening the valve system and two torque levels in the experiment. The four methods are: actuating the handwheel using bare hands only; actuating the handwheel repetitively up to 2/3rd of a turn using a conventional wrench; actuating the handwheel continuously using a conventional wrench; actuating the handwheel continuously using a modified wrench. All methods will be performed at two different torque levels 15 Nm (11.06 ft-lb) and 30 Nm (22.13 ft-lb). There will be a rest period of approximately 5 minutes; however, if you desire a longer rest period, it will be provided. The time to complete each trial (fully open the valve) will be measured. After each trial, you will be asked to rate your perceived physical exertion of the technique using a Borg-scale. It is estimated that this project will last up to two hours.

 Project 2a Study Procedures (males only): In this project, you will be asked to exert a maximal isometric torque on a static handwheel at various heights and angles. The heights will include knee, elbow, shoulder, and overhead level. The handwheel angles will include 0^o, 45^o, and 90^o. Three exertions will be performed at each height-angle combination. Each repetition will be separated by 30 to 60 seconds of rest and each set (height-angle combination) will be separated 2 minutes of rest. You will be connected to an EMG device to measure muscle activity. Eight adhesive electrodes will be attached on several trunk and shoulder muscles. If you desire a longer rest period, it will be provided. The maximal torque exertions and EMG activity of trunk and shoulder muscles will be measured. This project will take up to two hours to complete.

 Project 2b Study Procedures: In this project, you will be asked to exert a maximal isometric torque on a static handwheel at various heights and angles. The heights will include knee, elbow, shoulder, and overhead level. The handwheel angles will include 0^o, 45^o, and 90^o. Three exertions will be performed at each height-angle combination. Each repetition will be separated by 30 to 60 seconds of rest and each set (height-angle combination) will be separated 2 minutes of rest. If you desire a longer rest period, it will be provided. The maximal torque exertions will be measured. This project will take up to one hour to complete.

Benefits: There are no direct benefits; but this experiment may provide information that will yield future improvements in the task of opening and closing valve wheels through improved tools, standards, and/or workplace modifications.

Risks/Discomforts: There may be some discomfort during performance of the tasks which may lead to fatigue and/or aching of the muscles. The tasks have been designed to fall within the normal job performance for a chemical plant operator, so the potential physical discomfort is not expected to be any greater than that after a difficult work session. Participants are encouraged to inform the experimenter if discomfort or pain occurs.

Right to Refuse: At any time during the experiment, you have the right to not participate or withdraw from the study. There will be no penalties for withdrawal.

Privacy: The LSU Institutional Review Board (which oversees university research with human participants) may inspect and/or copy the study records.
Results of the study may be published, but no names or identifying information will be included in the publication.
Other than as set forth above, participant identity will remain confidential unless disclosure is legally compelled.

Financial Information: No costs are incurred by participants in this study.

Removal: You are expected to comply with the investigator's instructions. If you fail to comply, you will be removed by an investigator from the experiment.

Signatures: The study has been discussed with me and all my questions have been answered. I may direct additional questions regarding study specifics to the investigators. If I have questions about participant's rights or other concerns, I can contact Robert C. Mathews, Institutional Review Board, (225) 578-8692. I agree to participate in the study described above and acknowledge the investigator's obligation to provide me with a signed copy of the consent form.

____ __________________
Participant Signature Date

____
Print name

APPENDIX D: BORG-SCALE AND TIME FORM

Name: __________________ Gender: ________

Age: ____ Weight (lb): ____ Height: ____

How would you rate the physical intensity of each method using the Borg-scale (below)? Look at the verbal expressions first and then choose the corresponding number. For instance, if your perceived exertion is “difficult,” then you would put a rating of 5 in the table below, and if your perceived exertion is “very light,” then you would put a rating of 1. Base your ratings solely on how you personally perceive it to be, without considering the thoughts of others.

Rating of Perceived Exertion
10 point scale

0 - Nothing at all
1 - Very light
2 - Fairly light
3 - Moderate
4 - Some what difficult .
5 - difficult
6
7 - Very difficult
8
9
10 - Very, very difficult

Method	Borg Rating	Time (sec)
15 BH		
15 CW Restricted		
15 CW Unrestricted		
15 MW		
30 BH		
30 CW Restricted		
30 CW Unrestricted		
30 MW		

APPENDIX E: MAXIMUM TORQUE EXERTION FORM

Name: ___________________ Gender: ________

Age: ____ Weight (lb): ____ Height: ____

		Torque Exertion (ft-lb)			
Height	Angle	1	2	3	4
Overhead	90				
	45				
	0				
Shoulder	90				
	45				
	0				
Elbow	90				
	45				
	0				
Knee	90				
	45				
	0				

APPENDIX F: DATA

RC Data

Subject	1	2	3	4	5	6	7	8
Gender	Male	Male	Male	Male	Male	Male	Male	Male
Age (yr)	22.0	24.0	24.0	28.0	27.0	24.0	24.0	18.00
Height (in)	71.0	71.0	69.0	69.0	72.0	70.0	70.0	68.00
Weight (lb)	176.0	130.0	172.0	182.0	190.0	154.0	180.0	185.00

EMG (V)								
RC Method	1	2	3	4	5	6	7	8
R. Del Literature	0.0003050	0.0001580	0.0002100	0.0001300	0.0004050	0.0005000	0.0004350	0.0005000
R. Del Proposed	0.0003800	0.0003830	0.0005700	0.0004200	0.0005700	0.0006000	0.0007300	0.0005200
L. Del Literature	0.0001800	0.0001300	0.0001800	0.0001100	0.0003500	0.0003800	0.0004450	0.0005750
L. Del Proposed	0.0003070	0.0004150	0.0004750	0.0004300	0.0003900	0.0004300	0.0004300	0.0005650
R. Trap Literature	0.0001404	0.0005600	0.0005000	0.0006300	0.0006000	0.0001490	0.0006050	0.0004450
R. Trap Proposed	0.0011250	0.0009850	0.0004800	0.0005300	0.0008200	0.0007700	0.0006000	0.0007700
L. Trap Literature	0.0002204	0.0005100	0.0004600	0.0005550	0.0003450	0.0000850	0.0007300	0.0005150
L. Trap Proposed	0.0013800	0.0008500	0.0004900	0.0004800	0.0003720	0.0006900	0.0008200	0.0006800

Project-1 Data

DEMOGRAPHIC INFO															
Subject No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Gender	Male	Male	Male	Male	Male	Male	Male	Male	Male	Male	Male	Male	Male	Male	Male
Age	30.0	22	20.0	22.0	22	22.0	22.0	22	24	24.0	28	27	24	24	18
Height (in)	69.5	68.0	71.0	75.0	70.0	74.0	73.0	71	71	69.0	70	72	70	70	68
Weight (lb)	170.0	167.0	175.0	212.0	235.0	162.0	240.0	176	130	172.0	182	190	154	180	185

BORG																
Torque	Method\Subject	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
15 Nm	BH	2.7	4	2	3	4	4	2	4	5	1	9	1	3	7	2.5
	CW-R	1	5.5	3	2.5	3	0.5	1	4	4	5	9	3	4	6	3.5
	CW-U	2.5	4.5	2	2	3	1.7	2	4.5	2	2	4	1	1	5	2
	MW	1.5	3	2	2	2.5	2.4	1.5	3	4	1	3	1	1	3	0.5
30 Nm	BH	7	4.8	8	7	6.5	5	4	7.5	9	4	8	3	6	8	3
	CW-R	2	4.2	7	5	8	2.5	3	6	7	5	9	4	4	6	4
	CW-U	4.5	4.5	4	6	5.5	3	2.5	8	6	3	6	2	4	5	3
	MW	3	4.5	5	4.5	7.5	3.3	3.5	7	5	2	2	2	4	4	1

TIME (SEC)																
Torque	Method\Subject	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
15 Nm	BH	36	34	35.5	37	30.2	13.5	23.2	41	42	46	49	32	36.3	34.6	23
	CW-R	100	125	82	65	68.9	52	59	111	103	85	113	89	63.6	86.9	92
	CW-U	24	23	19	19	21.4	12	15.8	22	26	25	28	21	21.2	29.8	28
	MW	23	19	22	20	21.2	12.5	16	21	27	19	27	21	19.1	21.6	21
30 Nm	BH	54	45	36.5	42	33.2	22.2	27.7	46	115	67	38	41	48.9	40.1	24
	CW-R	122	92	81	59	58.5	48.3	83.1	116	90	108	124	116	84	70.5	107
	CW-U	36	32	22.8	23	19.8	13.8	19.8	26	45	35	27	27	32	27.2	45
	MW	32	39.2	25.7	20	24	12.1	21.7	23	35	24	16	22	24.7	36.1	26

RIGHT ANTERIOR DELTOID (%RC)																
Torque	Method\Subject	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
15 Nm	BH	63.9	90.8	53.4	52.2	53.2	105.0	40.3	70.0	159.6	13.0	55.4	46.9	41.5	63.9	44.4
	CW-R	60.0	34.5	60.0	62.5	72.7	43.5	54.1	88.9	69.4	54.0	60.0	30.4	58.4	68.3	46.1
	CW-U	65.3	115.2	72.2	47.3	77.9	98.9	82.4	115.5	99.1	74.8	87.0	48.7	62.6	114.3	77.0
	MW	48.9	101.5	55.1	40.4	62.8	85.4	99.6	67.5	69.8	59.5	68.5	65.7	58.3	108.6	112.4
30 Nm	BH	84.3	93.8	66.6	30.6	77.1	126.8	55.9	129.0	129.3	33.0	41.3	50.3	83.8	82.2	73.0
	CW-R	55.6	107.8	74.0	33.1	64.8	101.1	73.9	82.2	167.0	120.9	71.7	55.3	75.5	75.8	76.0
	CW-U	62.5	113.7	78.3	32.5	80.1	132.6	81.0	113.6	134.3	89.7	49.8	56.5	66.7	110.2	152.7
	MW	36.1	118.4	67.4	24.2	93.8	132.7	95.5	126.4	135.5	79.6	66.6	61.4	97.3	88.9	108.5

LEFT ANTERIOR DELTOID (%RC)																
Torque	Method\Subject	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
15 Nm	BH	10.3	20.4	7.8	18.2	22.1	44.0	24.8	12.5	20.1	8.5	19.0	19.8	12.2	21.1	23.0
	CW-R	23.6	58.0	37.3	101.9	85.9	58.4	45.7	37.6	112.0	42.7	26.1	35.5	73.3	86.0	41.1
	CW-U	24.1	87.9	27.9	43.2	108.5	82.8	58.6	109.9	116.5	45.0	37.1	47.3	23.6	40.1	53.6
	MW	34.3	10.7	28.3	31.6	64.5	72.5	52.7	93.9	124.1	49.3	41.5	48.9	49.0	67.1	83.5
30 Nm	BH	10.7	23.4	14.5	2.6	21.1	42.2	27.6	22.2	24.6	5.6	14.9	72.2	14.8	41.4	24.7
	CW-R	32.7	104.7	29.1	67.8	90.8	89.9	88.5	37.0	119.2	54.4	46.0	61.7	57.2	93.5	54.1
	CW-U	26.4	95.3	51.5	11.7	96.6	97.5	80.2	98.5	107.3	52.5	32.0	106.3	36.6	78.0	66.2
	MW	46.2	105.4	55.2	52.2	89.3	91.4	86.3	95.6	132.6	52.3	27.7	23.4	59.7	87.5	39.1

RIGHT TRAPEZIUS (%RC)																
Torque	Method\Subject	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
15 Nm	BH	26.2	22.3	15.2	42.9	36.5	86.5	31.3	32.3	48.0	1.3	61.5	47.1	27.6	40.1	21.3
	CW-R	11.3	18.5	7.5	33.9	22.8	24.7	13.8	38.1	42.1	4.1	35.8	12.3	35.8	33.2	23.8
	CW-U	47.9	22.0	27.4	31.1	83.3	98.2	39.7	95.5	96.2	22.7	54.0	30.3	58.5	127.3	67.7
	MW	30.8	41.9	22.8	30.0	30.5	96.9	43.9	61.0	61.0	21.9	43.3	40.9	50.8	87.8	87.7
30 Nm	BH	25.4	26.9	14.2	44.9	38.7	89.0	44.6	28.7	65.7	6.8	31.4	40.6	45.3	44.7	40.8
	CW-R	12.1	24.4	15.3	25.0	61.3	25.0	47.7	33.9	64.0	8.5	10.6	20.8	53.4	36.6	37.1
	CW-U	43.7	31.4	10.4	33.5	63.5	64.3	38.7	68.4	107.6	24.9	29.0	49.8	60.9	107.0	70.1
	MW	28.7	22.2	7.6	36.5	30.9	101.9	63.5	54.7	157.6	25.4	22.7	42.6	64.7	80.1	80.1

LEFT TRAPEZIUS (%RC)																
Torque	Method\Subject	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
15 Nm	BH	14.6	23.5	9.1	18.5	52.4	91.4	3.1	7.2	13.2	5.8	25.8	19.3	7.4	19.7	31.1
	CW-R	12.3	18.9	15.6	19.1	60.9	31.4	1.1	8.8	66.2	5.4	18.9	8.6	49.5	31.0	35.0
	CW-U	26.6	73.2	30.3	32.5	73.9	94.8	5.5	23.4	100.8	40.8	35.0	41.5	39.6	88.1	101.7
	MW	68.6	9.7	46.9	27.4	77.5	132.8	21.7	16.8	88.9	68.1	83.4	44.0	52.7	122.7	83.8
30 Nm	BH	19.7	24.1	7.6	14.5	70.0	100.1	7.5	18.9	16.7	14.7	36.9	24.6	10.8	33.9	35.2
	CW-R	20.4	15.2	16.0	18.2	32.3	57.3	12.9	5.3	97.1	26.2	15.5	12.4	52.3	43.3	39.6
	CW-U	44.9	59.9	22.7	23.3	78.3	133.4	3.8	25.8	99.9	46.2	41.6	29.1	45.8	118.3	73.3
	MW	84.8	50.5	59.1	42.6	88.2	172.7	66.4	58.8	112.3	69.5	103.1	38.7	59.1	90.0	63.8

RIGHT LATISSIMUS DORSI (%RC)																
Torque	Method\Subject	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
15 Nm	BH	25.3	39.6	45.8	19.9	13.9	30.3	42.5	37.6	95.2	28.5	108.8	42.9	17.1	26.3	21.5
	CW-R	9.9	26.3	35.1	34.3	24.5	14.9	23.2	26.3	67.8	29.0	74.9	12.6	8.3	6.3	11.8
	CW-U	16.3	38.2	38.7	37.2	28.3	21.8	28.5	36.5	163.4	42.2	69.3	15.7	16.1	6.8	34.6
	MW	18.7	132.6	29.0	24.8	19.6	22.3	38.4	18.9	100.6	44.6	200.8	18.2	14.4	16.5	14.8
30 Nm	BH	21.5	39.5	35.4	123.9	14.4	34.4	36.2	17.5	68.0	12.0	27.5	21.0	52.9	32.6	33.5
	CW-R	15.0	49.2	43.7	79.3	33.5	26.4	34.1	25.6	119.6	45.2	66.9	13.0	16.1	13.6	22.7
	CW-U	23.1	61.3	56.1	75.6	39.5	30.9	25.4	44.0	179.1	42.9	42.0	36.1	37.0	15.8	36.5
	MW	22.6	62.8	41.5	84.6	33.3	33.4	26.7	23.5	57.3	79.9	66.5	40.5	23.1	10.7	26.8

LEFT LATISSIMUS DORSI (%RC)																
Torque	Method\Subject	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
15 Nm	BH	72.2	57.0	81.3	62.3	45.9	30.4	120.2	128.7	62.4	15.4	35.6	49.2	26.7	73.1	72.9
	CW-R	28.1	44.7	51.2	84.2	36.9	11.7	106.6	34.5	25.2	13.2	32.8	16.5	30.8	19.9	23.7
	CW-U	26.2	40.9	59.7	105.8	40.8	12.6	68.9	105.6	32.7	58.8	51.9	12.5	23.5	20.1	82.9
	MW	30.4	38.1	50.2	29.4	36.6	21.7	97.3	79.1	51.2	71.4	17.9	20.7	24.7	35.3	38.1
30 Nm	BH	90.3	107.5	110.9	43.8	55.5	38.9	142.1	183.7	103.2	19.5	61.1	52.4	69.0	100.9	91.5
	CW-R	59.6	43.0	78.1	47.4	30.8	32.9	78.8	53.9	44.0	33.8	17.5	21.1	31.2	29.1	37.7
	CW-U	71.3	62.3	64.0	49.4	94.3	19.7	47.0	158.2	46.7	107.7	34.0	31.5	73.9	31.0	40.1
	MW	90.2	65.2	63.8	96.4	56.6	22.5	112.2	129.7	77.0	108.6	33.6	31.4	63.7	61.0	62.0

RIGHT ERECTOR SPINAE (%RC)																
Torque	Method\Subject	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
15 Nm	BH	46.0	29.7	28.0	40.1	40.4	33.1	46.7	40.6	40.3	24.6	57.1	24.2	47.2	80.5	33.4
	CW-R	33.1	29.2	34.2	58.5	39.9	38.1	46.1	58.2	44.2	105.7	43.4	34.4	64.2	59.5	33.1
	CW-U	63.9	50.2	37.8	56.4	39.9	49.3	90.7	117.5	54.8	44.7	79.6	44.7	64.5	66.8	45.1
	MW	53.5	29.5	36.6	50.8	37.1	48.8	79.2	104.0	51.3	51.7	68.7	55.4	52.2	63.8	46.6
30 Nm	BH	39.6	30.7	29.1	34.0	41.7	42.2	51.0	68.9	35.8	23.7	46.6	27.7	40.1	108.5	40.4
	CW-R	40.2	33.9	33.0	51.3	31.5	33.6	46.4	55.6	49.3	48.7	47.7	35.7	54.3	69.9	30.3
	CW-U	55.1	64.4	34.3	70.2	40.1	53.7	90.7	143.3	55.9	57.9	66.0	78.7	55.3	65.6	50.5
	MW	50.3	52.6	38.5	66.3	25.1	59.0	77.8	137.7	51.5	70.7	60.6	38.0	48.1	57.9	45.2

LEFT ERECTOR SPINAE (%RC)																
Torque	Method\Subject	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
15 Nm	BH	36.2	22.2	26.1	64.9	33.6	51.2	49.0	36.8	45.0	7.2	84.0	31.1	62.7	170.0	44.6
	CW-R	28.0	21.0	38.7	80.3	30.8	42.4	42.2	64.2	49.9	152.1	49.0	22.0	54.1	69.8	27.3
	CW-U	37.9	34.3	23.2	45.7	84.8	73.5	66.6	112.8	57.4	59.1	71.8	33.3	58.5	67.9	42.4
	MW	39.4	28.1	26.5	46.2	48.9	50.5	61.7	91.4	47.7	55.4	59.8	54.9	50.3	93.5	38.6
30 Nm	BH	36.8	21.6	37.3	52.0	46.6	61.8	68.2	55.4	59.3	18.3	88.5	34.3	79.3	102.5	39.1
	CW-R	42.0	24.9	32.4	61.7	36.1	41.7	60.5	71.9	54.9	74.2	53.1	26.3	60.2	67.4	31.0
	CW-U	41.2	41.9	33.6	54.9	58.8	67.5	84.0	94.1	73.6	83.0	78.1	75.4	78.5	113.4	48.4
	MW	43.1	36.3	31.3	57.3	55.9	76.9	91.5	92.9	77.2	73.6	78.7	51.9	65.3	85.1	42.4

Project-2 Data (Demographic Information and Maximum Torque Data in ft-lb)

Info\Subject	1	2	3	4	5	6	7	8	9	10
Gender	Male	Male	Male	Male	Male	Male	Male	Male	Male	Male
Age	30.0	21.0	22.0	20	20.0	20.0	22.0	21	22.0	20.0
Height (in)	69.5	69.0	71.0	64.0	70.0	68.0	67.0	70.0	70.0	71.0
Weight (lb)	170.0	135.0	176.0	151.0	164.0	171.0	172.0	151.0	180.0	175.0

Info\Subject	11	12	13	14	15	16	17	18	19	20
Gender	Male	Male	Male	Male	Male	Male	Male	Male	Male	Male
Age	37.0	21.0	22.0	22.0	24.0	21.0	22.0	26.0	25.0	23.0
Height (in)	70.0	72.0	74.0	70.0	68.0	70.0	70.5	68.0	75.0	70.0
Weight (lb)	225 lb	163 lb	168.4 lb	200 lb	140 lb	165 lb	175 lb	230 lb	200.0	175 lb

Info\Subject	21	22	23	24	25	26	27	28	29	30
Gender	Male	Male	Male	Male	Male	Male	Male	Male	Male	Male
Age	22.0	29.0	22.0	24.0	24.0	28.0	27.0	24.0	24.0	18
Height (in)	69.0	71.0	70.0	71.0	69.0	69.0	72.0	70.0	70.0	68
Weight (lb)	223 lb	206.0	214.0	130.0	172.0	182.0	190.0	180.0	154.0	185

Info\Subject	31	32	33	34	35	36	37	38	39	40
Gender	Female	Female	Female	Female	Female	Female	Female	Female	Female	Female
Age	22.0	22	22	24	24	26	23	22	25	25
Height (in)	67.0	63	64	64	66	64	66	66	63	60
Weight (lb)	130	190	150	131	155	102	142	150	122	100

Info\Subject	41	42	43	44	45	46	47	48	49	50
Gender	Female	Female	Female	Female	Female	Female	Female	Female	Female	Female
Age	25	28	28	22	22	27	30	19	36	21
Height (in)	65	62.5	67	61	61	71	68	65	63	67
Weight (lb)	121	116.8	140	115	114	155	131	110	215	141

Info\Subject	51	52	53	54	55	56	57	58	59	60
Gender	Female	Female	Female	Female	Female	Female	Female	Female	Female	Female
Age	21	20	26	35	21	20	20	20	20	29
Height (in)	69	63	67	71	63	64	63	67	65	66
Weight (lb)	125	110	115	200	135	130	124.5	142	125	137.5

Height	Angle\Subject	1	2	3	4	5	6	7	8	9	10
	90	90.6	81.9	65.9	56.2	70.2	35.7	52.2	56.7	61.2	81.5
	45	93.5	86.0	60.4	59.4	64.2	36.3	60.6	50.7	56.7	80.5
Overhead	0	62.4	48.2	40.8	41.8	49.8	30.9	47.7	44.8	40.6	53.6
	90	88.1	81.6	50.4	66.5	65.7	32.1	63.4	50.9	51.8	77.0
	45	82.2	77.3	73.5	51.4	65.2	31.1	59.8	54.4	62.8	76.7
Shoulder	0	77.8	61.9	49.8	50.1	60.0	31.8	63.8	55.6	53.3	74.4
	90	93.1	54.7	49.6	72.9	54.5	40.2	45.3	51.0	50.3	62.2
	45	96.1	69.4	72.5	71.6	60.0	34.1	47.1	56.0	43.5	65.5
Elbow	0	86.2	57.6	57.4	64.3	66.0	37.5	55.8	56.9	43.7	76.1
	90	81.1	66.2	64.5	54.6	59.1	39.9	60.5	42.3	48.9	59.3
	45	76.6	54.7	48.2	49.8	51.6	33.7	45.5	47.1	40.8	62.5
Knee	0	91.2	80.0	67.4	52.8	46.0	34.1	42.6	45.8	40.5	75.1

Height	Angle\Subject	11	12	13	14	15	16	17	18	19	20
	90	98.5	65.2	38.5	45.6	65.6	88.4	76.5	73.9	59.4	58.1
	45	96.0	57.0	33.7	44.7	67.2	82.2	80.4	74.9	59.8	53.0
Overhead	0	82.9	45.0	22.0	33.3	46.3	53.8	57.0	84.1	44.2	45.3
	90	97.6	67.9	24.7	71.1	48.6	81.9	75.8	86.1	75.3	53.2
	45	108.1	58.0	27.1	58.8	58.0	70.2	73.6	79.0	58.3	47.2
Shoulder	0	92.8	56.3	30.5	42.4	45.0	79.2	75.1	65.5	43.4	45.7
	90	91.5	50.9	29.2	45.9	53.1	68.1	77.1	71.3	50.2	52.3
	45	87.1	55.6	33.2	46.0	44.8	72.4	78.8	77.0	48.9	53.0
Elbow	0	91.7	46.2	33.4	35.0	45.0	64.9	85.1	78.9	55.3	53.1
	90	106.6	62.0	30.4	42.8	53.2	69.3	82.5	85.6	47.9	54.8
	45	94.3	56.7	34.2	37.6	45.3	65.6	71.7	76.3	50.7	56.8
Knee	0	99.8	55.1	32.2	35.6	52.2	79.6	100.4	77.0	50.6	50.7

Height	Angle\Subject	21	22	23	24	25	26	27	28	29	30
	90	96.8	79.6	103.2	70.2	87.5	78.0	84.3	82.5	66.8	81.2
	45	98.1	82.7	93.7	80.8	107.7	99.2	84.0	70.4	71.8	85.1
Overhead	0	66.9	59.2	64.4	35.4	69.4	58.9	60.4	76.5	40.0	66.3
	90	90.0	87.0	71.1	70.2	79.0	77.0	95.8	86.9	72.6	84.4
	45	101.5	83.3	84.6	60.5	65.1	106.2	92.2	65.3	59.0	91.8
Shoulder	0	83.0	77.7	75.4	53.5	70.4	81.9	82.9	52.3	68.4	79.2
	90	73.8	84.5	76.0	52.5	55.0	69.6	68.1	68.5	39.4	82.3
	45	80.9	81.8	83.4	58.1	56.5	75.7	72.3	86.6	52.9	85.3
Elbow	0	84.3	84.5	99.1	58.3	62.6	87.2	91.1	86.2	73.8	96.9
	90	77.0	84.8	73.8	56.3	64.4	72.0	71.2	101.4	51.7	81.7
	45	74.5	75.5	71.1	50.9	63.0	52.3	70.3	81.9	42.8	74.5
Knee	0	56.7	78.3	72.7	43.7	92.2	67.2	72.5	99.9	52.2	79.1

Height	Angle\Subject	31	32	33	34	35	36	37	38	39	40
Overhead	90	37.8	44.0	23.6	58.9	54.5	27.0	33.7	45.5	43.5	35.1
	45	34.9	39.7	34.7	68.7	44.6	33.8	37.3	47.2	46.9	32.0
	0	23.9	30.4	25.3	43.2	27.2	20.5	23.3	26.3	20.1	16.9
Shoulder	90	38.8	35.1	32.8	52.2	52.6	37.4	40.2	46.4	36.5	21.8
	45	35.1	36.6	31.2	61.3	47.3	40.4	29.9	44.2	27.0	27.4
	0	32.9	29.5	33.1	56.6	58.5	28.6	30.9	41.0	27.0	25.8
Elbow	90	34.6	32.9	32.0	35.8	40.8	23.2	25.5	38.4	30.7	19.0
	45	32.0	38.4	31.6	55.8	46.7	18.8	27.5	40.3	39.6	19.5
	0	36.1	33.5	32.4	67.1	42.4	26.4	29.4	45.7	37.5	21.0
Knee	90	33.3	35.7	30.7	49.6	41.5	29.4	24.9	38.8	30.8	27.4
	45	22.4	32.2	31.0	39.0	43.5	26.8	25.7	38.6	30.9	25.8
	0	22.2	38.1	32.0	51.9	42.6	39.5	33.6	47.4	34.1	30.4

Height	Angle\Subject	41	42	43	44	45	46	47	48	49	50
Overhead	90	17.5	27.2	19.1	23.5	19.0	61.5	31.6	27.8	46.8	50.9
	45	15.4	28.8	24.6	26.3	22.6	52.5	28.5	35.0	42.9	56.2
	0	8.7	20.3	11.3	17.5	13.8	31.2	18.9	22.0	36.1	37.4
Shoulder	90	15.4	29.3	15.2	18.9	22.4	53.6	26.2	34.5	37.1	58.8
	45	15.8	23.1	13.4	18.5	27.7	38.4	32.2	33.6	40.6	52.9
	0	13.0	22.0	16.2	19.9	19.7	51.8	31.1	34.1	48.3	45.8
Elbow	90	15.4	20.1	16.6	19.7	18.1	43.7	24.5	24.8	34.0	41.6
	45	14.8	21.0	18.0	19.2	26.1	43.7	26.4	30.3	36.1	47.2
	0	14.7	24.3	22.0	24.4	28.0	39.0	27.1	32.6	42.8	52.4
Knee	90	16.7	24.3	21.7	21.0	18.7	40.6	26.1	31.6	35.3	40.6
	45	15.8	22.0	16.3	17.8	13.5	39.1	25.4	26.3	35.8	42.6
	0	15.0	24.1	15.3	23.3	15.7	42.6	30.1	43.9	40.8	62.5

Height	Angle\Subject	51	52	53	54	55	56	57	58	59	60
Overhead	90	17.7	31.7	27.9	27.7	38.6	41.5	47.5	31.1	43.0	50.7
	45	18.2	32.2	26.9	35.2	41.6	46.0	50.3	32.0	39.4	69.4
	0	16.0	21.5	16.6	20.5	21.5	23.8	29.1	26.0	34.0	29.9
Shoulder	90	13.4	38.5	28.5	32.9	30.1	35.4	49.7	42.5	46.8	56.0
	45	14.9	30.9	27.9	31.6	32.8	35.6	50.0	42.0	45.1	60.8
	0	15.6	30.3	28.1	34.2	31.4	25.2	47.5	38.2	46.3	44.3
Elbow	90	16.6	29.5	26.7	26.5	35.8	34.8	32.3	31.3	37.4	28.3
	45	15.8	28.6	27.4	26.7	28.9	31.1	44.0	32.4	39.0	52.9
	0	17.9	31.8	27.2	21.4	32.7	48.5	43.2	36.7	42.6	53.4
Knee	90	20.8	39.0	35.8	34.7	29.3	33.1	26.3	37.0	49.7	45.4
	45	16.1	19.9	25.5	32.4	26.3	30.6	40.1	29.3	38.8	50.8
	0	14.2	47.8	28.4	37.6	25.2	36.3	47.5	34.1	47.7	64.6

Project-2 Data (Demographic Information and EMG activity)

Info\Subject	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Gender	Male	Male	Male	Male	Male	Male	Male	Male	Male	Male	Male	Male	Male	Male	Male
Age	30.0	18.0	20	20.0	20.0	22.0	21	22.0	20.0	24.0	24.0	28.0	27.0	24.0	24.0
Height (in)	69.5	68.0	64.0	70.0	68.0	67.0	70.0	70.0	71.0	71.0	69.0	69.0	72.0	70.0	70.0
Weight (lb)	170.0	185.0	151.0	164.0	171.0	172.0	151.0	180.0	175.0	130.0	172.0	182.0	190.0	154.0	180.0

Right Anterior Deltoid (%RC)																
Height	Angle\Subject	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Overhead	90	116.5	133.1	108.5	119.0	153.2	199.0	93.5	135.5	77.3	144.3	72.2	67.0	95.9	67.5	134.1
	45	79.6	141.8	20.9	104.5	60.8	244.7	91.5	103.3	66.2	142.9	65.8	60.8	52.5	48.6	127.7
	0	11.8	20.9	51.8	61.8	10.7	45.0	26.5	6.0	9.1	20.7	14.4	22.0	17.9	2.6	12.6
Shoulder	90	93.9	111.7	91.6	69.0	98.0	301.1	84.4	72.9	35.2	113.5	44.7	38.4	58.8	59.1	86.9
	45	108.4	99.2	61.6	74.1	33.0	232.7	63.0	62.7	41.8	122.2	40.5	88.5	59.0	69.2	70.5
	0	68.4	115.9	49.8	70.0	51.5	39.1	45.3	39.1	47.9	87.3	39.3	7.6	63.0	50.8	78.6
Elbow	90	59.7	33.2	57.9	35.1	51.1	49.5	63.0	19.9	10.7	67.7	22.5	7.6	2.0	19.3	52.9
	45	96.7	90.9	92.4	47.4	67.5	39.2	60.8	69.1	19.1	115.3	33.9	8.2	18.1	56.8	94.6
	0	96.7	131.8	72.9	68.9	81.6	151.0	65.0	69.0	48.0	102.1	25.2	21.5	53.8	45.5	60.4
Knee	90	41.5	64.9	34.5	24.9	41.5	47.4	20.3	7.3	6.9	15.6	34.6	3.8	19.3	10.6	41.1
	45	113.9	105.4	83.3	61.3	205.3	157.4	55.6	64.9	32.6	69.8	55.9	38.4	61.9	34.6	101.3
	0	105.3	80.1	85.0	86.2	161.3	154.1	87.0	125.7	46.2	129.6	49.5	71.5	52.0	47.4	140.6

Left Anterior Deltoid (%RC)																
Height	Angle\Subject	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Overhead	90	35.7	37.7	27.3	15.2	9.8	13.9	49.0	23.1	4.6	25.7	27.9	6.9	45.3	6.9	103.5
	45	104.8	11.8	14.1	37.5	6.9	93.0	45.4	30.2	14.4	23.2	24.9	22.1	38.4	11.5	87.6
	0	74.0	45.7	125.0	116.9	56.3	114.4	103.7	76.1	23.9	24.7	34.7	18.7	68.2	107.4	10.6
Shoulder	90	6.1	11.2	6.6	9.8	9.0	15.4	11.4	7.9	5.3	7.2	8.6	2.0	4.6	5.0	4.9
	45	16.7	6.7	11.4	15.3	69.1	26.0	26.7	12.3	3.2	13.0	23.5	7.6	5.4	8.1	24.1
	0	23.1	25.4	21.1	34.3	9.9	31.4	48.6	18.8	8.5	13.2	16.8	22.8	18.2	34.6	24.6
Elbow	90	28.0	37.1	8.6	30.1	5.2	8.2	24.4	11.9	31.5	4.0	8.1	13.2	43.3	6.5	4.6
	45	18.1	10.1	5.3	12.0	3.5	7.3	6.9	6.2	8.9	4.0	3.4	4.2	4.5	4.5	7.3
	0	18.1	9.4	10.0	9.8	4.9	10.6	5.4	10.6	3.8	3.7	5.6	2.9	3.6	4.4	4.2
Knee	90	29.7	23.1	7.5	24.1	10.0	13.9	5.4	4.9	5.8	5.8	7.4	4.8	9.2	3.7	159.6
	45	7.6	8.5	5.3	7.0	16.9	10.9	11.1	5.7	1.6	4.5	7.9	4.8	4.1	5.2	26.5
	0	6.2	18.9	5.4	5.3	8.5	43.3	8.6	6.0	2.8	7.8	10.9	4.2	5.5	5.0	11.4

Right Trapezius (%RC)																
Height	Angle\Subject	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Overhead	90	70.3	43.8	39.8	50.1	41.9	36.6	48.2	67.8	17.7	67.4	55.7	49.9	76.0	79.7	89.3
	45	80.0	50.5	17.5	23.5	29.7	30.6	57.6	34.1	9.6	50.0	13.6	20.1	30.2	36.1	49.8
	0	14.8	14.8	18.5	69.5	10.5	5.4	18.0	3.0	4.3	16.2	7.1	13.1	18.4	47.5	18.9
Shoulder	90	39.0	55.1	28.6	47.1	22.8	62.4	47.8	16.8	32.7	35.8	45.5	22.9	64.5	38.4	50.1
	45	56.1	75.8	17.4	67.5	20.2	14.3	51.5	16.5	16.2	43.2	25.5	27.0	73.4	34.8	76.7
	0	24.5	18.3	23.6	39.0	24.2	21.6	28.5	30.9	41.7	41.2	26.4	24.5	14.7	36.2	65.1
Elbow	90	63.1	75.6	47.2	23.7	33.9	14.4	29.2	18.8	5.7	39.2	28.6	27.2	25.9	28.2	60.5
	45	82.1	47.0	28.5	35.1	19.2	45.7	28.6	15.4	14.2	25.6	28.2	11.5	57.1	45.6	19.7
	0	34.1	4.7	15.9	10.1	25.2	58.3	30.7	31.8	14.6	23.3	18.6	19.8	32.3	37.8	36.3
Knee	90	60.1	65.1	29.5	52.9	29.6	53.5	16.3	17.8	15.3	26.5	75.1	25.3	33.1	50.3	57.0
	45	61.4	89.5	32.5	49.0	43.4	48.0	40.8	27.2	11.5	61.3	58.0	45.0	59.0	47.9	28.8
	0	25.9	82.7	11.4	34.6	38.9	3.8	17.3	16.2	7.6	51.3	17.7	23.1	36.9	39.4	92.0

Left Trapezius (%RC)																
Height	Angle\Subject	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Overhead	90	67.7	56.6	10.8	13.1	25.4	2.6	18.9	43.5	20.0	30.5	69.3	4.2	20.1	44.9	93.6
	45	84.9	62.3	14.8	27.5	31.5	10.4	21.5	31.7	14.6	39.3	31.3	24.2	70.2	8.2	75.0
	0	50.3	99.2	52.5	58.3	64.1	40.0	49.0	25.2	21.6	52.5	83.1	34.4	67.3	102.2	79.5
Shoulder	90	9.6	5.9	11.8	4.8	9.6	29.8	18.8	16.6	6.3	11.8	25.5	5.5	7.7	5.3	3.7
	45	59.4	41.7	12.2	39.4	36.0	2.8	48.4	12.4	7.5	20.8	29.8	23.0	20.3	22.4	58.8
	0	30.7	68.2	25.0	56.6	18.3	20.1	29.4	24.9	32.3	26.8	38.5	42.2	19.6	52.9	81.5
Elbow	90	13.9	47.1	37.0	6.3	4.5	2.6	8.4	9.4	2.5	15.4	14.0	3.2	4.9	2.7	3.7
	45	27.6	5.1	8.6	5.3	3.7	3.3	3.3	12.3	3.5	8.7	14.8	5.7	28.0	2.9	4.3
	0	31.2	3.8	5.7	5.1	19.8	2.8	12.4	11.6	4.6	9.1	25.7	14.0	12.3	7.0	5.1
Knee	90	5.9	5.4	1.6	6.4	3.4	4.2	3.4	2.7	2.4	4.4	36.0	3.5	3.8	2.9	34.4
	45	12.9	5.9	15.2	5.7	10.7	5.0	16.5	3.5	2.0	13.8	8.5	5.2	4.7	4.1	5.7
	0	6.6	30.1	2.5	5.2	4.8	2.9	4.0	2.0	3.0	1.4	13.0	3.9	6.5	2.5	9.7

Right Latissimus Dorsi (%RC)																
Height	Angle\Subject	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Overhead	90	24.7	11.3	35.4	55.9	32.8	42.1	57.8	67.8	9.7	42.7	35.6	34.6	23.1	11.9	4.6
	45	15.9	14.2	45.6	71.3	13.7	32.4	60.0	44.9	7.4	66.5	21.8	16.6	13.4	11.9	3.9
	0	38.2	15.2	33.1	59.4	20.9	45.1	80.5	64.9	12.1	79.1	19.0	28.2	19.7	34.4	23.3
Shoulder	90	12.0	12.0	20.2	24.1	7.7	31.1	31.0	21.3	11.1	37.2	18.6	19.6	8.6	10.8	4.5
	45	14.3	14.1	18.7	20.7	147.9	27.4	33.3	22.2	11.2	35.0	10.7	23.6	9.4	8.7	9.7
	0	7.5	14.5	13.6	19.2	10.9	51.7	28.2	18.3	7.4	18.0	11.6	21.1	13.4	8.4	4.0
Elbow	90	19.2	60.3	54.9	36.0	9.7	61.8	22.6	16.8	53.1	18.7	10.5	14.3	61.3	29.0	19.1
	45	16.3	12.2	32.3	12.2	8.8	23.6	22.5	29.4	16.7	37.2	11.3	21.8	23.7	23.3	11.4
	0	11.2	15.1	25.9	26.7	16.3	48.7	19.0	25.3	13.7	20.6	12.2	17.9	5.2	27.0	11.1
Knee	90	36.6	35.1	21.0	49.0	26.0	18.8	57.2	23.5	19.2	21.6	10.6	28.5	21.6	32.5	70.7
	45	49.2	14.2	28.3	38.2	68.0	26.5	73.7	47.4	9.0	25.5	43.9	19.5	15.9	10.4	6.7
	0	34.4	17.5	29.6	37.6	26.6	21.8	62.5	74.1	9.3	55.3	23.1	25.2	12.1	9.8	8.0

Left Latissimus Dorsi (%RC)																
Height	Angle\Subject	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Overhead	90	81.1	28.4	11.6	81.6	34.4	74.0	55.2	81.8	57.5	25.3	42.0	22.0	29.8	51.0	19.9
	45	32.7	7.3	9.9	19.6	57.0	58.9	25.8	34.8	61.0	20.1	26.7	6.1	11.6	46.1	15.2
	0	51.6	25.9	16.5	27.4	29.1	90.0	56.5	26.6	19.4	35.3	19.8	15.1	14.5	20.2	35.0
Shoulder	90	107.4	159.4	29.9	43.3	67.0	278.5	108.4	80.2	146.0	44.3	60.0	110.7	101.6	99.2	80.0
	45	123.6	170.4	16.7	33.8	21.3	122.7	181.1	69.0	114.4	54.9	23.2	36.3	183.7	39.2	70.2
	0	45.1	41.3	13.7	14.7	40.2	81.0	27.1	37.3	28.4	22.7	20.2	9.7	16.8	13.2	22.4
Elbow	90	147.1	87.9	63.7	71.8	110.4	63.9	190.4	104.4	73.7	85.5	43.5	99.5	27.6	96.8	80.7
	45	191.4	212.0	83.9	79.7	144.0	135.8	234.5	201.3	181.3	146.4	50.7	139.7	119.1	112.2	118.0
	0	153.3	210.0	84.1	86.2	267.6	131.4	308.7	119.9	273.7	122.6	23.4	125.8	128.4	83.0	118.5
Knee	90	61.9	43.5	15.6	31.1	26.0	158.0	30.1	34.5	111.4	13.1	26.7	17.8	10.5	19.1	13.7
	45	103.5	97.8	31.9	49.9	100.0	251.4	46.7	131.9	212.8	33.9	64.8	73.1	33.2	82.5	100.3
	0	103.3	55.2	19.7	56.1	117.0	182.9	114.4	140.4	199.5	57.5	31.8	35.1	59.9	78.9	142.7

Right Erector Spinae (%RC)																
Height	Angle\Subject	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Overhead	90	14.6	16.5	13.3	12.6	5.6	9.4	13.3	9.3	8.9	5.0	17.8	16.2	7.7	5.2	20.7
	45	10.7	10.1	17.8	14.1	5.3	7.6	9.6	8.6	9.1	3.1	12.5	20.8	4.8	19.4	32.3
	0	67.2	16.0	41.0	44.0	18.9	10.3	27.8	21.9	14.3	3.7	31.3	23.9	16.0	4.8	73.0
Shoulder	90	12.6	35.3	15.4	15.3	10.0	11.1	13.7	16.6	5.2	3.9	8.8	13.4	15.5	7.3	7.0
	45	30.4	28.6	14.1	29.1	13.2	12.6	23.4	11.3	8.0	4.2	10.0	32.6	9.2	10.0	34.2
	0	25.6	37.7	35.4	27.0	9.3	14.5	7.9	11.7	12.9	3.7	10.7	22.1	12.7	55.0	48.6
Elbow	90	15.7	43.5	16.7	19.5	11.4	9.0	24.7	10.3	23.9	3.1	15.6	11.9	8.0	30.8	34.8
	45	20.6	17.6	22.2	28.1	6.7	6.1	20.3	17.7	18.0	4.0	17.8	27.7	13.5	32.9	79.8
	0	48.5	59.4	32.5	39.4	13.6	7.0	32.8	12.1	21.5	9.6	24.3	31.0	18.1	44.0	88.0
Knee	90	72.3	58.1	56.8	31.4	52.7	12.6	8.3	30.8	16.2	24.6	17.3	13.7	9.5	20.0	91.1
	45	115.0	21.6	40.7	37.1	132.7	9.7	25.8	25.5	7.9	27.4	12.7	23.6	16.6	16.4	15.7
	0	34.7	104.3	32.0	35.3	12.1	14.5	4.7	31.1	29.0	8.7	6.4	27.6	10.4	27.8	10.9

Left Erector Spinae (%RC)																
Height	Angle\Subject	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Overhead	90	24.5	17.9	34.5	49.7	24.5	18.2	17.6	15.4	27.1	12.7	78.8	11.0	12.3	22.5	94.6
	45	9.0	14.0	25.5	24.7	15.6	26.2	19.9	6.1	30.8	5.9	62.4	20.4	18.2	12.9	46.7
	0	13.4	13.4	14.4	24.4	9.0	9.1	28.9	6.2	12.0	5.1	58.2	9.7	15.7	7.1	43.1
Shoulder	90	27.8	57.1	31.8	52.0	60.6	33.2	49.3	15.1	18.8	16.6	44.8	48.8	40.3	31.4	23.1
	45	25.6	43.5	29.9	54.1	40.4	13.8	43.1	6.9	29.1	11.4	21.9	22.1	31.5	28.7	48.3
	0	9.5	31.7	17.6	27.6	27.8	13.5	11.8	5.0	12.8	10.1	25.7	9.8	11.7	15.2	56.6
Elbow	90	65.3	60.4	55.4	53.8	35.1	73.2	47.4	19.9	45.7	30.0	30.9	28.0	24.9	57.0	72.4
	45	77.5	44.9	45.8	49.8	24.0	21.6	50.2	14.5	45.3	14.4	25.6	35.7	36.8	65.1	92.6
	0	41.7	41.4	37.0	48.9	23.9	22.3	71.4	25.7	37.3	15.9	21.6	31.6	41.3	67.5	70.0
Knee	90	51.3	45.9	37.8	38.6	10.8	25.0	21.5	34.2	46.4	48.3	51.2	9.7	3.9	41.1	82.7
	45	57.0	26.0	41.1	36.2	119.8	20.9	60.2	31.9	31.8	52.3	34.6	57.1	37.9	33.9	9.4
	0	38.0	48.7	36.3	38.7	13.1	22.0	24.4	29.9	38.4	51.9	25.7	31.3	25.0	27.5	38.8

APPENDIX G: SAS PROGRAM

RC SAS Program

```
dm 'output;clear;log;clear';
title1 “Saif Al Qaisi, Statistical Analysis of RCs”;
options nodate nocenter pageno=1 ls=78 ps=55;
ods rtf;
Data DVdata;
Infile cards missover;
Input P M$ DV;
cards;
*input data here*
;
proc print;
title2 “EMG for the different RC methods”;
run;
proc ttest data=DVdata;
class M;
var DV;
run;
ods rtf close;
quit;
```

Project-1 SAS Program

```
dm 'output;clear;log;clear';
title1 “Saif Al Qaisi, Statistical Analysis of Dynamic Strength Project”;
options nodate nocenter pageno=1 ls=78 ps=55;
ods rtf;
Data DVdata;
Infile cards missover;
Input P T$ M$ DV;
cards;
***Input Data here***
;
proc print;
title2 “Data for the different torques and methods used”;
run;
proc mixed;
title2 “Mixed procedure”;
Class P T M;
model   DV = T|M  /  ddfm  =  kr  ;
random   P  P*T  ;
lsmeans T|M  / pdiff adjust=tukey;
ods output diffs=ppp lsmeans=mmm;
run;
```

```
%include 'C:\pdmix800.sas';
%pdmix800 (ppp,mmm,alpha=0.05,sort=yes);
ods rtf close;
quit;
```

Project-2 SAS Program (Includes Gender Factor)

```
dm 'output;clear;log;clear';
title1 “Saif Al Qaisi, Statistical Analysis of Static Torque Project”;
options nodate nocenter pageno=1 ls=78 ps=55;
ods rtf;
Data DVdata;
Infile cards missover;
Input G$ P H$ A$ DV;
cards;
***Input Data here***
;
proc print;
title2 “Data for the different heights and angles”;
run;
proc mixed;
title2 “Mixed procedure”;
Class G P H A;
model   DV = G|H|A  /  ddfm  =  kr  ;
random   P(G)    H*P(G)  ;
lsmeans G|H|A  / pdiff adjust=tukey;
ods output diffs=ppp lsmeans=mmm;
run;
%include 'C:\pdmix800.sas';
%pdmix800 (ppp,mmm,alpha=0.05,sort=yes);
ods rtf close;
quit;
```

Project-2 SAS Program (Excludes Gender Factor)

```
dm 'output;clear;log;clear';
title1 “Saif Al Qaisi, Statistical Analysis of Static Project EMG”;
options nodate nocenter pageno=1 ls=78 ps=55;
ods rtf;
Data DVdata;
Infile cards missover;
Input P H$ A$ DV;
cards;
***Input Data here***
;
proc print;
title2 “Data for the different heights and angles”;
run;
```

```
proc mixed;
title2 “Mixed procedure”;
Class P H A;
model   DV = H|A  /  ddfm  =  kr  ;
random   P    H*P     ;
lsmeans H|A  / pdiff adjust=tukey;
ods output diffs=ppp lsmeans=mmm;
run;
%include 'C:\pdmix800.sas';
%pdmix800 (ppp,mmm,alpha=0.05,sort=yes);
ods rtf close;
quit;
```

VITA

Saif Al-Qaisi was born in Amman, Jordan in 1987. During most of his childhood, he lived in Baton Rouge, Louisiana, where he received his elementary and high school education. He earned his undergraduate degree in Industrial Engineering from Louisiana Tech University (Ruston, Louisiana), in August 2008.

Upon graduation, he joined the Industrial Engineering program at Louisiana State University (LSU) to pursue a Master of Science degree with a concentration in Human Factors. At LSU, he worked as a teaching and research assistant (TA and RA) in the Industrial Engineering program. As a TA, he was the lab instructor for the Human Factors Engineering Lab and Occupational Biomechanics Lab for four years. Also, he served as a TA for five additional industrial engineering courses. As an RA, he coauthored eight publications that include refereed journal articles and conference proceedings. He completed his Master Degree in Industrial Engineering with a minor in Applied Statistics in August 2012.

He continued his education at LSU, pursuing a Doctorate Degree in Engineering Science with a major in Industrial Engineering and a concentration in Human Factors. During this period, he served as a TA and an RA in the department of Mechanical and Industrial Engineering. He expects to receive the degree of Doctor of Philosophy in May 2013.